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A Modern Teaching Environment for Process Automation

Master's Programme in Chemical, Biochemical and Materials Engineering
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Abstract of master's thesis

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Abstract

Emergence of the new technological trends such as Open Platform Communications Unified Architecture (OPC UA), Industrial Ethernet, cloud computing and the 5th wireless network (5G) enabled the implementation of Cyber-physical System (CPS) with flexible, configurable, scalable and interoperable business models. This provides new opportunities for the process automation systems. On the other hand, the constant urge of industries for cost and material efficient processes demands a new automation paradigm with the latest tools and technologies which should be taken into account while teaching future automation engineers.

In this thesis, the modern teaching environment for process automation is designed, implemented and described. This work explains the connections, configurations and the test of three mini plants including the Multiple Heat Exchanger, the Three-tank system and the Mixing Tank. In addition, OPC UA communication between the server and its clients has been tested. The plants are a part of the state of the art of the architecture that provides the access of ABB 800xA to the cloud services via OPC UA over the 5G test wireless network. This new paradigm changes the old automation hierarchy and enables the cross layered communication in the old architecture.

This modern teaching environment prepares the students for the future automation challenges with the latest tools and merges data analytics, cloud computing and wireless network studies with process automation. It also provides the unique chance of testing the future trends together in this unique process automation setup.

Keywords: Educational Setup, Industial Ethernet, Cloud Computing, 5G, OPC UA, CPS, FoF

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Contents

Abbreviations

6LoWPAN	IPv6 over the Low-Power Wireless Personal Area Network
AIDC	Automatic Identification and Data Capture
5G	5th wireless generation
AI	Analog Input
AIIC	Aalto Industrial internet Campus
AML	AutomationML, Automation Markup Language
ANSI/ISA	International Society for Automation
AO	Analog Output
API	Application Program Interface
ARIMA	Autoregressive integrated moving average
ARM	Architectural Reference Model
AS	Automation System
B2MML	Business To Manufacturing Markup Language
BPA	Business Process Automation
BPM	Business Process Management
CAEX	Computer Aided Engineering Exchange
CC	Cloud Computing
CCSA	China Communication Standards Association
CEN	European Committee for Standardization
CENELEC	European Committee for the Electro technical Standardization
CIM	Common Information Model
CMCR	The Central Monitoring and Control Room
CMCS	The Central Monitoring and Control System
CoAP	Constrained Application Protocol
COM	Component Object Model
CoRE	Constrained RESTful Environments
CPS	Cyber-Physical Systems
CPU	Central Processing Unit
CS	Computer Science
CSA	The Cloud Security Alliance
CSMA	Carrier Sense Medium Access
CSP	Cloud Service Provider
CV	Control Valve
CYPROS	Cyber-Physical Production Systems
DaaS	Data as a Service
DAQ	Data Acquisition
DBES	Databricks Enterprise Security
DCOM	Distributed Component Object Model
DCS	Distributed Control System
DDS	Data Distribution Service
DI	Digital Input
DNS	Domain Name Server
DO	Digital Output

DSL	Domain-specific Language
EDDL	Electronic Device Description Language
EFM	Electric Field Mapping
EIS	Embedded Internet System
EPC	Engineering, Procurement & Construction
ERP	Enterprise Resource Planning
ETSI	European Telecommunications Standards Institute
EWMA	Exponentially weighted moving average
FBD	Function Block Diagram
FCS	Fieldbus Control System
FDI	Field Device Integration
FDMA	Frequency-Division Multiple Access
FDT/DTM	Field Device Tool/ Device Type Management
FoF	Factory of Future
GARCH	Generalized autoregressive conditional heteroskedastic
HMI	Human-Machine Interface
HTTP	Hypertext Transfer Protocol
IaaS	Infrastructure as a Service
IAB	The Internet Architecture Board
ICS	Industrial Control System
ICT	Information and Communication Technologies
IEC	The International Electro technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IESG	The Internet Engineering Steering Group
IETF	Internet Engineering Task Force
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IIRA	Industrial Internet reference Architecture
IL	Instruction List
IMT	International Mobile Telecommunications
IOE	Internet of Everything
IOMOG	Assetricity Integrated Operations and Maintenance for Oil & Gas
IoS	Internet of Services
IoT	Internet of Things
IoT-A	Internet of Things - Architecture
IP	Internet Protocol
IPS	Indoor Positioning System
IRTF	Internet Research Task Force
ISA-95	International Society of Automation standard 95
ISBM	Information Service Bus Model
ISO	International Organization for Standardization
ISoc	Internet Society
ITU	International Telecommunication Union
JDBC	Java Database Connectivity
KPI	Key Performance Indicators
LAN	Local Area Network
LD	Ladder Diagram

LR-WPAN	Low-Rate Wireless Personal Area Networks
M2M	Machine-to-Machine
MaaS	Metal as a Service
MES	Manufacturing Execution System
MIMOSA	Machinery Information Management Open Systems Alliance
MPC	Model Predictive Control
MST	Manufacturing Science and Technology
MTU	Master Terminal Unit
MVC	Model View Controller
NFC	Near Field Communication
NIST	National Institute of Standards and Technology
O&G	Oil and gas
ODBC	Open Database Connectivity
OIC	Open Interconnect Consortium
OLE	Object Linking and Embedding
OPC	OLE for Process Control
OPC UA	OPC Unified Architecture
OSI	Open System Interconnection
OWL	Ontology Web Language
P&ID	Piping and Instrumentation Diagram
PA	Process Automation
PaaS	Platform as a Service
PAS	Process Automation Systems
PERA	Purdue Enterprise Reference Architecture
PFD	Process Flow Diagram
PLC	Programmable Logic Controller
PSE	Production System Engineering
PTT	Push-to-Talk
QoS	Quality-of-Service
RaaS	Routing as a Service
RAM	Random Access Memory
RAMI 4.0	Reference Architectural Model for Industrie 4.0
RDD	Resilient Distributed Dataset
RFID	Radio Frequency Identification
RPA	Robotic Process Automation
RRI	Reader to Reader Interference
RTI	Reader to Tag Interference
RTU	Remote Terminal Unit
SaaS	Software as a Service
SAP	Systems, Applications and Products
SCADA	Supervised Control And Data Acquisition
SCL	Substation Configuration Language
SDK	Software Development Kit
SecaaS	Security as a Service
SFC	Sequential functional chart
SIG	Bluetooth Special Interest Group
SIL	Safety Integrity Level

SIS	Safety Instrumentation System
SM	Smart Manufacturing
SMLC	Smart Manufacturing Leadership Coalition
SOA	Service-Oriented Architectures
SQL	Structured Query Language
ST	Structured Text
TCP	Transmission Control Protocol
TDMA	Time-Division Multiple Access
UDP	User Datagram Protocol
UI	User Interface
UID	User Interface Description
UIP	User Interface Plug-In
UML	Unified Modelling Language
WfaaS	Workflow as a Service
VoIP	Voice over IP
VPN	Virtual Private Network
VPS	Virtual Private Server
WSN	Wireless Sensor Networks
XaaS	Anything as a Service
XML	Extensible Markup Language

Figures

Tables

1. Introduction

We live in a new automation epoch in which robots and computers can perform a wide range of activities better and more efficiently than humans. The automation activities can promise productivity growth and other benefits at both the level of an individual process and businesses, as well as the level of entire economies where productivity acceleration is solely needed (Manyika *et al.*, 2017).

The new trends of process automation are showing the key role of increasing connections to have more real-time data collection and advanced analytical computation for improving performance, reducing operating costs and increasing reliability (ARC Advisory, 2015). According to the McKinsey Global Institute report on emerging technologies, by 2025 there will be $36 and $1.7 trillion potential economic impact on automation criteria including Internet of Things and Cloud Technologies respectively (Marrs, Bisson and Dobbs, 2013). Therefore, it is concluded that process automation paradigm should be changed by the utilization of the new tools and technologies to respond to the constant urge of industries for more efficient processes.

The above-mentioned statements clear the importance of training the engineers to pick up the pace towards modern automation. This thesis aims to set up a modern teaching environment for chemical engineers with the state of the art architecture. The architecture utilizes the latest frameworks and tools for the engineers and enables the 5G wireless network prototype.

The literature review discusses on the current state of process automation and the progressive changes of the automation hierarchy. In this part, the development of the new hierarchies affected by Cloud Computing, the Cyber-physical System and the Factory of the Future are discussed. They are aimed to present a compatible hierarchy with the modern automation which contributes to an ever increasing wireless connectivity at the production level. Moreover, OPC UA and other standards for information modeling of the architecture are explained.

The experimental part presents the modern automation architecture and proceeds with detailing its elements. As a part of the architecture, this setup has three smart pilot plants in its field level to test different continuous and batch processes. Furthermore, the field level connections and configuration in ABB 800xA control system are described. The experimental part also explains the installation and the test of OPC Unified Architecture as the communication tool. Finally, the discussion and conclusions outline the implementation, difficulties of the experiments and the outcome of this work.

LITERATURE REVIEW

2. Process Automation

Process Automation (PA) has had the three different generations which Table 1 presents as the so-called before automation control (ancient), automation systems before computers (16th – 1940) and computer automatic control (1940 – present) (Melik-Merkumians *et al.*, 2012). Fig. 1 shows the development of the process automation systems from the 18th century with mechanical automation to the recent times by the computer aided control systems.

Table 1. Automation Generations (Melik-Merkumians *et al.*, 2012)

Generation	**Type**	**Example**
Before Automation Control		Waterwheel
Automation Control before Computers (16th – 1940)		Automobile
Computer Automation Control (1940 – present)	Hydraulic Automation Pneumatic Automation Electrical Automation Electronic Automation Micro Automation Nano Automation Mobile Automation Remote Automation	Hydraulic elevator Door open/shut Telegraph Microprocessor Digital Camera Nano memory Cellular Phone Global Positioning Systems

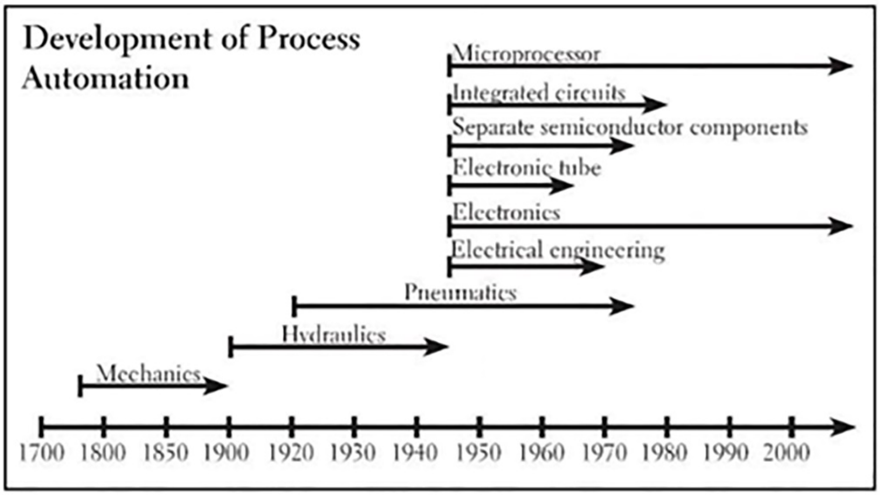

Figure 1. Development of Process Automation

Table 1 and Fig. 1 present important trends such as mobile and remote automation as well as microprocessors and integrated circuits. These trends shape the basis of current and future of process automation. Additionally, Table 1 shows that in the 20th century with the emergence of computer automation control, the complication of the process automation systems increased and categorized into three main divisions.

The first one is the *Business Process Automation* (BPA) which is used as a tool for Business Process Management (BPM) to link automation and redesigning, to measure performance and workflow, to bring the language of business in line with the IT language and to make Enterprise Resource Planning (ERP) robuster (Bocher and Valdes, 2013). The second category is *Robotic Process Automation* (RPA) which tries to perform routine business processes by mimicking human / software interaction and to substitute human workforce with robots. These are a part of the spectrum of emerging artificial intelligence tools and machine learning technology (Schatsky, Muraskin and Iyengar, 2016).

The third category is *Process Automation Systems* (PASs) which addresses the automatic control of industries such as chemical, oil & gas, metal & mineral, pulp and paper (ABB Group, 2010). It uses a network to interconnect sensors, actuators, controllers, operators and terminals. Unlike Distributed Control Systems (DCS), PAS follows open standards for communication and is associated with Supervisory Control and Data Acquisition (SCADA). PAS is positioned in the lowest level of automation and below the Manufacturing Execution System (MES). It aims at efficient processes in energy / material consumption, cost reduction and control equipment regulation (Kirrmann, 2009). The major parts of the PAS are the Analog and Digital I/O modules, SCADA, Remote Terminal Units (RTUs), micro / multi-processors and micro- controllers and computers. This thesis focuses on the third category or process automation systems to interconnect these major parts and to utilize them.

Process automation systems use the reference model architecture called Purdue Enterprise Reference Architecture (PERA) which is developed by Theodore J. Williams and the members of the Industry-Purdue University Consortium (Williams, Rathwell and Hong, 2001). Fig. 2 shows the architecture concept that became common since the 1990s. In this model, the level zero is designated for the actual production process or the field level, while the above level senses the production variables and manipulates them via the connection between PLCs and the sensors and actuators (ISA-95, 2005).

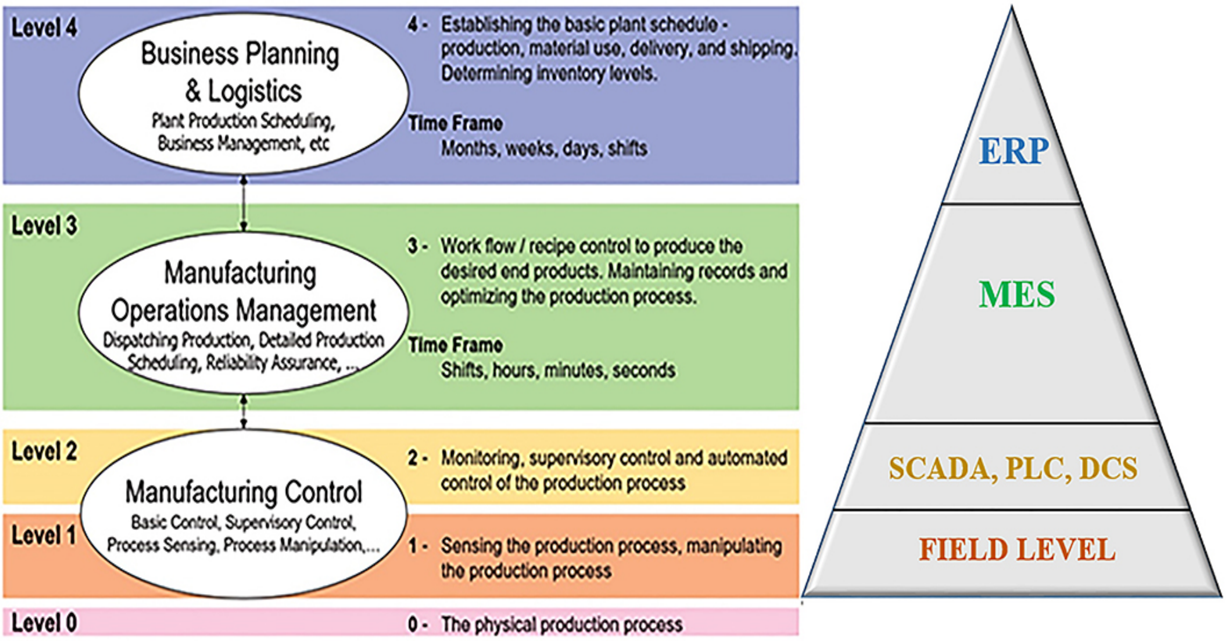

Figure 2. Purdue Enterprise Reference Architecture (ISA-95, 2005)

The level 2 is for monitoring and supervisory control. This level is presented as SCADA, DCS, and Programmable Logic Controller (PLC). Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) present the work flow / recipe control and establish the plant schedule, respectively (ISA-95, 2005). Table 2 presents the time frame work and the involved systems at different levels of PERA (ISA-95, 2005). This reference architecture was later adopted by ANSI/ISA-95 (ISA-95, 2005) and often referred as the Process Automation Hierarchy.

Table 2. The time framework of different levels in PERA

Level	Label	Time Frame
0	The Physical Process	-

1	Intelligent Devices	Lowest delay possible
2	Control Systems	Sub-seconds, Seconds, Minutes, Hours
3	Manufacturing Operations Systems	Seconds, Minutes, Hours, Shifts, Days
4	Business Logistics Systems	Days, Weeks, Months

The recent driving forces such as green and networked economies and technological trends and tools pave the way for new process automation. Therefore, businesses expect the benefits of sustainable development and optimized processes in the global competition by utilization these trends. In this respect, the next part presents the effects of the modern process automation on businesses at the macro and micro levels.

3. Effects of the Modern Process Automation on Businesses

Modern process automation potential has been analyzed on the global economy. McKinsey Global Institute reported that we can expect improvement in performance by reducing errors, and improvement in quality and speed. Furthermore, by 2055, there is potential to automate half of the people's activity that is paid almost $16 trillion in wages. However, people still need to continue to work alongside the machines (Manyika *et al.*, 2017).

McKinsey Global Institute raises the anticipation that the productivity growth will be at two levels. One, at the microeconomic level which encompasses individual processes and businesses and results in labor cost reductions, higher performance, increased throughput, higher quality and decreased downtime. Second, at the macroeconomic level that raises in productivity growth on a global basis by 0.8 to 1.4 percent, annually. These effects might be slow at the macro level within the entire sectors or economies and quite fast at the micro level which is at the workforce level (Manyika *et al.*, 2017).

The pace and the extent of modern automation will be determined by technical, economic and social factors (Manyika *et al.*, 2017) such as:

- Technical Feasibility: Technology has to be invented, integrated and adapted to solutions for a specific use case.
- Cost of developing & deploying solutions: Hardware and software costs, especially in developing stage.

- Labor Market Dynamics: The cost of human labor affects which activities will be automated i.e. if the work force is expensive, the activity is more potential to be automated.
- Economic Benefits: Higher throughput and increased quality decide where automation should be implemented.
- Regulatory and social acceptance: Adaption to modern automation requires time to be implemented in business.

As indicated by McKinsey, the new waves of technology change process automation and industries at micro and macro levels. However, such changes in process automation need to be compatible with emerging concepts like cloud, cyber-physical systems and the factory of the future. In this respect, the next part presents the latest changes of the process automation hierarchy which would result in more flexible paradigms.

4. Changes in the Process Automation Hierarchy

4.1. Important features of the current automation hierarchy

As discussed earlier, PERA model is used as the reference architecture in process automation. Fig. 3 shows the same hierarchy between ERP and Production Process layers where the information flows between these two points (Vogel-Heuser *et al.*, 2009). Moving from the bottom to the top, the spatial and the time scale of automation increase (Omer and Taleb, 2014) and the size of data packages, the frequency of transmission and real-time requirement decrease (Vogel-Heuser *et al.*, 2009).

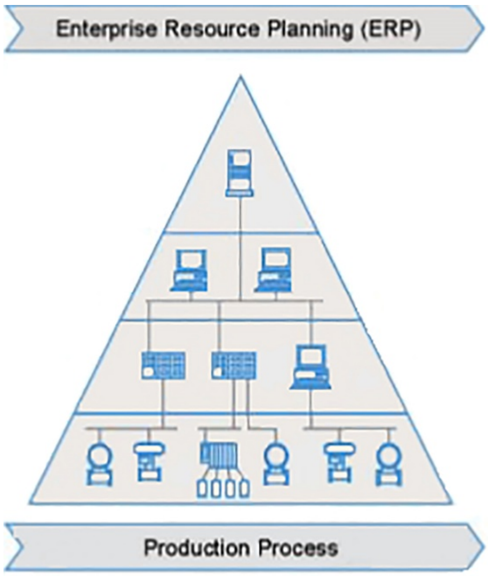

Figure 3. The information Pyramid of Automation (Vogel-Heuser *et al.*, 2009)

In the automation hierarchy, the product of each layer needs to be designed to transfer data with the upper or the lower layer and the given metaphor for such a feature is ‘Connector’. Therefore, the process automation system suppliers do not have any responsibility towards other layers except the neighboring layers. However, this limits the functionality of devices and makes district communication between different automation vendors (Vogel-Heuser *et al.*, 2009). Fig. 4 presents sets of standards that are categorized into models and technologies which glue the layers together (Karnouskos, Bangemann and Diedrich, 2009). In this figure, the most related features to this thesis are Extensible Markup Language (XML) from the models and OPC UA from the technologies.

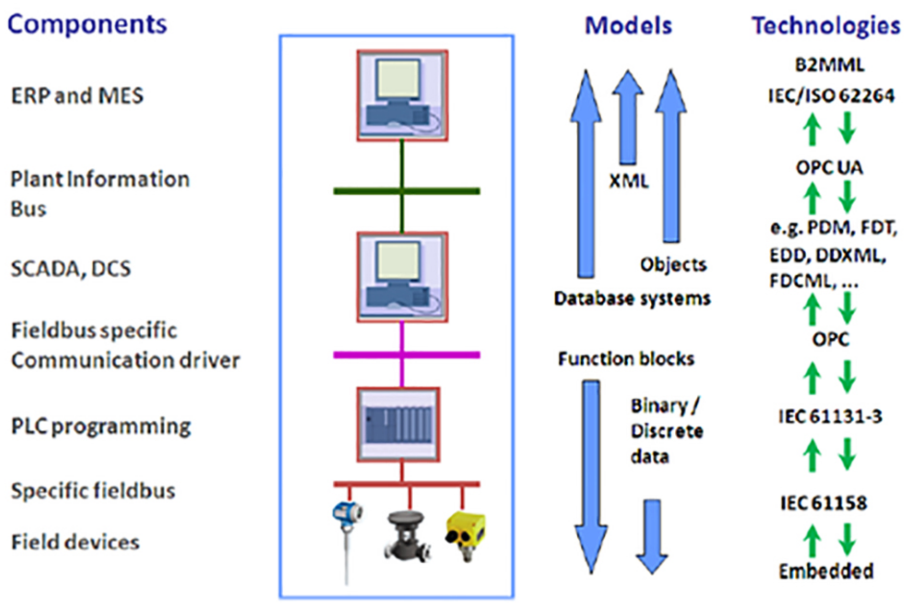

Figure 4. Standards and protocols for gluing the layers of the pyramid (Karnouskos, Bangemann and Diedrich, 2009)

Although some of the features of the current hierarchy like the layered concept bring limitations, but they provide vendors with device classification and modules to fit and design their products into a specific layer (Vogel-Heuser *et al.*, 2009). However, technologies like OPC UA promise a unified platform for process automation vendors to exchange data faster between devices. In the following part, some of the new technologies and demands are described.

4.2. Motivations and availabilities for modern process automation

Progressions in industry paved the way for more advanced process automation systems. In this part, automation related demands and availabilities are presented for two points of view such as Business Strategy and Production System Engineering (PSE).

From Business Strategy point of view, the trend has changed from a mass production system to a customer demanding and mass customization with a higher speed of production. It is estimated that the speed of production has increased 120% in terms of the needed time to deliver orders and 70% in time to transport the products to the markets (Davies, 2015; Melik-Merkumians *et al.*, 2012).

Shorter production cycles (Melik-Merkumians *et al.*, 2012), increased manufacturing flexibility and the constant need for an efficiency increment (Davies, 2015) are other affected trends that provoke new demands from process automation. Moreover, faster and easier procedures for selecting supplier is required since everything around manufacturing operation including the plant, distributors and the products are digitally connected.

Additionally, removing the complexity of time-consuming contracting and exclusive prices are other forces that motivate changes in automation and regulations (Davies, 2015). There are new engineering options that can be available to increase the capacity in the production systems, the options are:

- Field devices have become more intelligent and smart transmitters/ actuators have emerged with high computational power that includes maintenance support and asset management (Sendler, 2013).
- Changes at communication level have led to the development of devices from sensor/ actuator to Industrial Ethernet (Vogel-Heuser *et al.*, 2009).
- Fieldbus components have become more intelligent; hence they are capable of running their own small PLCs which have led to the decentralization of automation systems (Vogel-Heuser *et al.*, 2009).
- Device software have become more integrated. EDDL or FDT/DTM and Field Device Integration (FDI) are new tools for a unified operation, engineering, maintenance and information exchange (FDI Cooperation, 2012; Hadlich *et al.*, 2016).

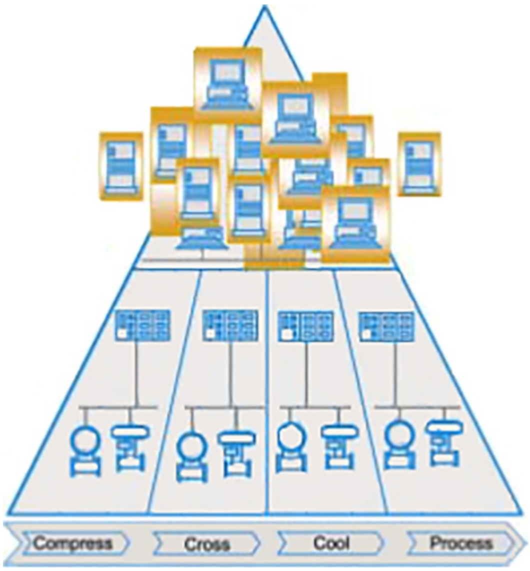

Figure 5. Automation pyramid affected by more intelligent devices (Vogel-Heuser *et al.*, 2009)

Fig. 5 shows the primary modification of automation pyramid with more intelligent devices and modular sub processes that is affected by the above-mentioned advances in PSE. In this figure, most of the upper layers are merged and potential to be replaced by the cloud space. Therefore, the next part discusses on the cloud-based automation architectures in different contexts and backgrounds.

4.3. Emerging cloud-based process automation hierarchy

Recently, the buzzwords like cloud computing (CC), the Factory of the Future (Smart Factories), Cyber-physical System (CPS), and Internet of Things (IoT) are widely used, albeit IoT is simply networking of these cyber-physical devices for information transfer and CPS is a holonomic system, which consists of physical entity and its cyber twin connected together (Pandhare, 2015). In this section, we focus on the changes of the process automation hierarchy from the window of CPS, the Factory of the Future and cloud computing.

Firstly, the basic concept of the automation hierarchy with cloud computing is discussed. Secondly, the automation hierarchy is presented from the Cyber-physical System point of view that is called ’CPS-based Automation’ and thirdly, the concepts of the Factory of the Future and the System of Systems are explained.

4.3.1 Automation hierarchy and cloud computing

According to Vogel-Heuser *et al.* (2009), the modularity of modern automation has become more integrated and affected its vertical aspect. The same integration concept applies to the manufacturing cells and production lines in the horizontal aspect. Fig. 6 shows these two aspects of information modelling that change the life cycle of production systems.

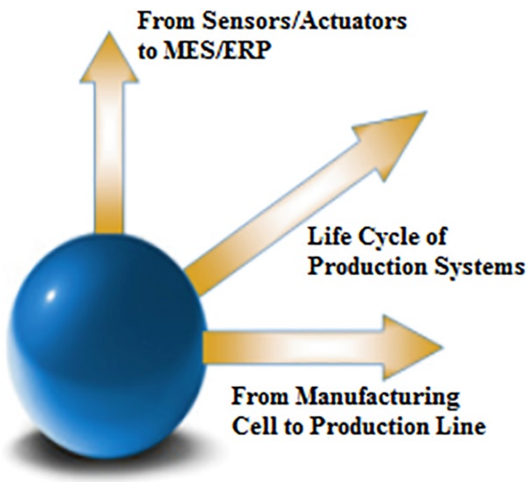

Figure 6. Dimensions of Integration in information model of automation (Vogel-Heuser *et al.*, 2009)

As Vogel-Heuser *et al.* (2009) mention, the top of the pyramid will migrate to cloud space (Fig. 7) and results in the first idea of a new automation model called the Double Cone or Diablo. Diablo can also take the acronym for Distributed Information Architecture to Bolster Lifecycle Optimization. This base architecture represents the concept of an automation architecture with two parts, which consists of the field device layer and the ERP.

Fig. 8 presents the same concept with the addition of the Information Model that binds the two parts together.

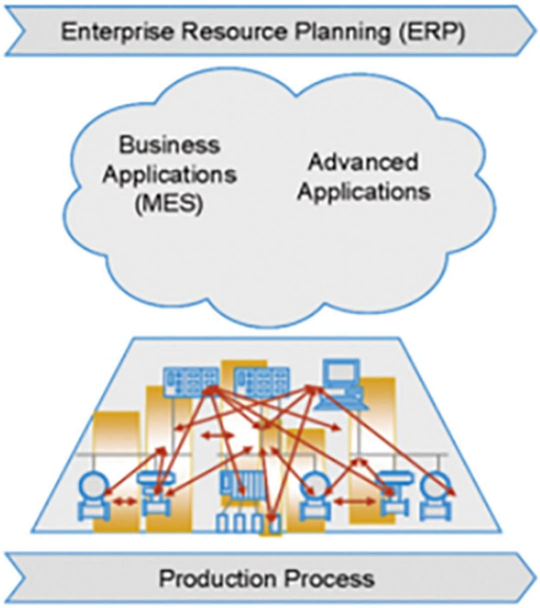

Figure 7. Migration of the automation layers into the cloud space (Vogel-Heuser *et al.*, 2009)

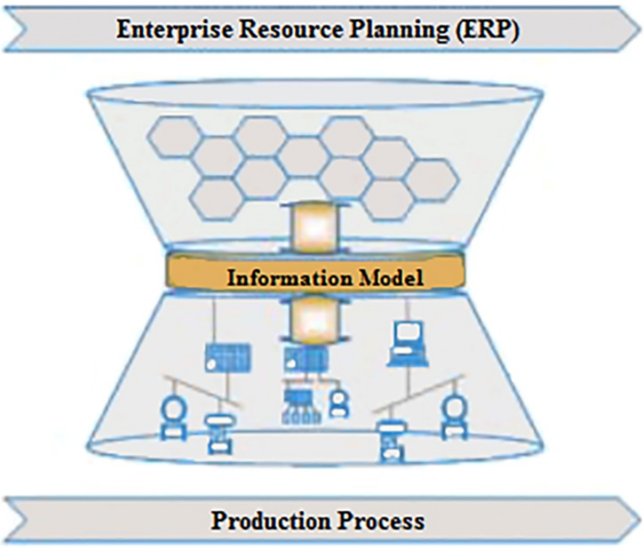

Figure 8. Information cone with the information model layer as a connecting layer (Vogel-Heuser *et al.*, 2009)

Givehchi and Jasperneite, (2013) bind two concepts that are derived from figures 6 and 8 and combine them with the cloud computing concept to propose a new process automation hierarchy (Fig. 9). The presented Global Information Architecture with the use of cloud computing consists of two main layers which are presented as two cones encompassed with Business and Technical Processes. However, the cloud is separated in two parts as alternatives: IT-Cloud and Automation Cloud, which both can offer their functions and services as ‘Software as a Service’ (SaaS). IT-Cloud hosts applications and services at the upper levels of automation while the Automation Cloud (AT-Cloud) offers functions and services at the lower levels. Moreover, the IT-Cloud and the AT-Cloud are integrated together by the information model that is located between them.

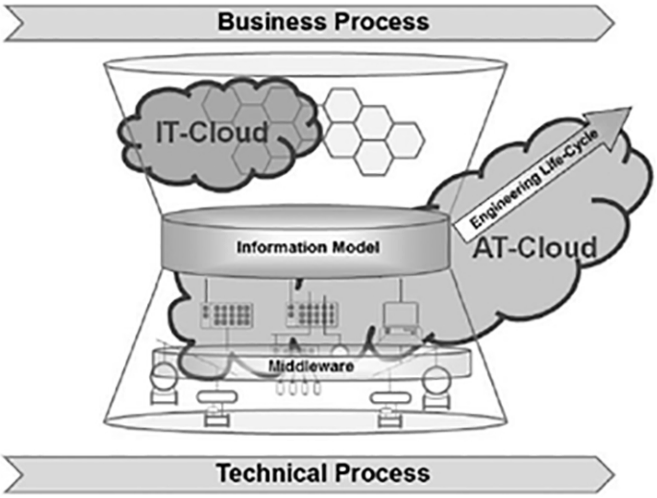

Figure 9. Global Information Architecture with the use of cloud computing (Givehchi and Jasperneite, 2013)

4.3.2 Automation hierarchy and cyber-physical systems

Fig. 10 presents the CPS-based automation (Givehchi and Jasperneite, 2013) as a modified architecture for the model proposed by Vogel-Heuser *et al.*, (2009). In this proposal, the information model is replaced with direct service interaction and as a result, the IT and Automation Clouds are substituted by CPS.

Services and functions are inside the delivery standards to enable the interaction between the cloud and the real devices. The hierarchy in Fig. 10 consists of two main parts such as the field device level which remains unchanged in the automation pyramid and the replacement of the non-physical functions and services with the cloud services (Givehchi and Jasperneite, 2013).

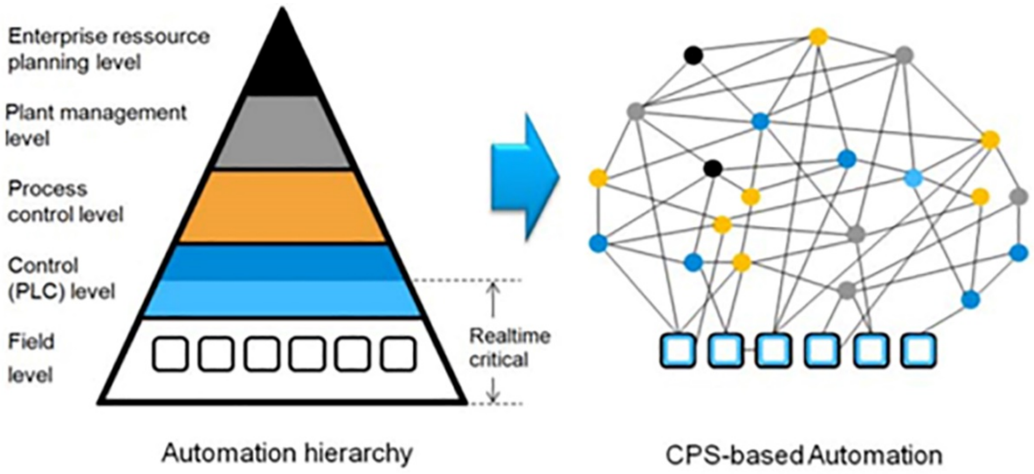

Figure 10. Decomposition of automation hierarchy by CPS & distributed services (Givehchi and Jasperneite, 2013)

In process automation, cloud computing applications can be categorized based on their focus on each individual level. Most of these applications aim to migrate functions and services to CPS-Based automation. Givehchi and Jasperneite (2013) present this division at the enterprise management level, process control level and field device level. The authors also consider cloud computing as a possible solution for the computing platform in information technologies such as Internet of Things, the SOA and mobile computing.

4.3.3 Automation hierarchy and the factory of the future

Karnouskos *et al.* (2014) propose a coherent architecture framework for the Factories of the Future (FoF) that relies on multi system interactions, collaborative cross layer management and automation approaches. Fig. 11 shows a Service-oriented Architecture (SOA) for monitoring, management and data handling that integrates web services, Internet Technology (IT), cloud systems and Internet of Things (IoT).

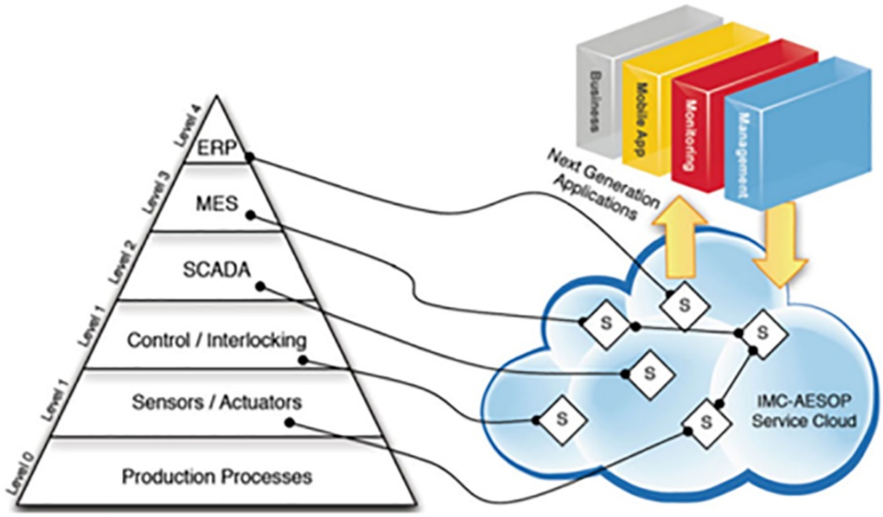

Figure 11. Industrial automation evaluation: complementing the ISA-95 (on the left) with a flat information-based infrastructure for dynamically compatible services and applications (right side) (Karnouskos *et al.*, 2014)

This approach proposes that the Factory of the Future is relied on the System of Systems (SoS) which leads to a large scale collaboration (Northrop *et al.*, 2006). The collaboration is realized as services in 'Service Cloud' and they are distributed, automated, intelligent and pro-active (Karnouskos *et al.*, 2014).

In this prospective, the Factory of the Future appeared as a new dynamic cyber-physical infrastructure with a wide range of scales from sensors to electronic components. However, with the enabled modern SOA (comparing with the old automation hierarchy), the functionalities of each system or devices can be offered as a service. Therefore, such a service can be hosted in the cloud and composed by other cross layered services. Fig. 11 shows the services of the old automation hierarchy that can be hosted in the cloud where applications such as management, monitoring, mobile app and business are accessed in other layers (Karnouskos *et al.*, 2014). The architecture is considered as a preliminary vision to the cyber-physical systems and in relation to the 4th industrial revolution (Industrie 4.0). Some of the architecture key roles are (Karnouskos *et al.*, 2014):

- Process Monitoring and Control
- Real-time Information Processing
- Scalability
- Backward/ Forward Compatibility
- Creation of Combinable Services and Tools
- Cross-layer Integration and Real-time Interaction
- Interoperability and Open Exchange Formats

Combing new elements like the cloud space with the automation hierarchy requires modification in the information flow models and the security features. These matters are essentially important since the pass of data exchange should be rerouted via cloud and data access becomes easier and faster. Thus, the next part unfolds the importance of information modelling and details on the OPC UA standard with its security features.

5. Standards and Information Modeling

Process automation standards define the information flow, device communication and data processing and presentation. However, there are many different challenges to model the data flow between nodes, devices and systems (Breivold and Sandström, 2015). Table 3 lists some of the organizations that model the data exchange in different systems by proposing protocols and new technologies (Lu *et al.*, 2016).

Table 3. Most important process automation standards

Organization Name	**Sub-groups**	**Focus**
OLE for Process Control Foundation (OPC Foundation)	OPC Unified Architecture	For incorporating all functionalities of OPC by using cross platforms, web services and other modern technologies
International Standard Organization (ISO)	SC4	Focuses on industrial data standards like ISO 10303 for the exchange of product manufacturing information. ISO 15926 for the integration of life-cycle data
	SC5	Focuses on interoperability, integration and architecture for automation applications
International Electro technical Commission (IEC)	IEC 62264	Standardized version of ISA-95 for integrated enterprise and control systems and manufacturing methods
	IEC 1131	Standard for process control software
	IEC TC65	Industrial process measurement, control and automation
International Society of Automation (ISA)	ISA-95	Developing and automated interface between enterprise and control systems
	ISA-99	Industrial automation and control systems security - the development of ISA/IEC 62443

IEEE Standards	C37.1-2007	The requirements for SCADA and automation systems in substations are defined. This standard defines the process of substation integration as the design process that is the foundation for substation automation

Among these standards, OPC UA uses cross platform, web service and many other new communication technologies to incorporate the functionalities of the old OPC and enables vertical and horizontal communication in the automation hierarchy to provide semantic interoperability for smart systems (Burke, 2015). In the following part, OPC UA and its association with the automation pyramid, cloud computing and ABB 800xA is explained. Furthermore, the OPC UA information model is presented and compared with the classic OPC.

5.1. OPC Unified Architecture

OPC Unified Architecture is released by OPC Foundation as an industrial data exchange standard for safe and reliable communication. By introducing the SOA architecture, OPC UA offered a scalable and independent platform where businesses can benefit from web services with integrated security (Burke, 2015). OPC UA provides solutions to be compatible with the new industrial revolution. Some of these features are:

- Independent form communication technology: OPC UA product development is membership-free and OPC UA is neutral in the technology sector. OPC UA is implemented in all languages including Ansi C/C++, .NET and Java. In addition, it runs on all operating systems (Burke, 2015).
- Horizontal and vertical communication across automation pyramid layers: OPC UA is scalable for integrated networks including smartphones, PCs, PLC controllers, cloud services and embedded systems (Burke, 2015).
- Secure transfer and authentication at user and application level: OPC UA uses username/ password authentication, signed and encrypted transfer (Burke, 2015).
- Data transport via TCP/IP for live and historic data exchange, HTTP/HTTPS web service with XML (Burke, 2015).
- OPC UA provides hierarchical and full meshed networking that includes big data and object oriented address spaces (Burke, 2015).

- OPC UA follows IEC 62541 and it has semantic expansion (Burke, 2015).

5.2. OPC UA and the automation pyramid

Fig. 12 shows the automation pyramid associated with OPC UA that follows the server/client technology. The former OPC UA was based on Microsoft-COM/ DCOM technology, but the new OPC UA became platform-independent by the state of the art of web service technology. Therefore, it is integrated with MES and ERP. Additionally, OPC UA has real-time capability for controllers and intelligent devices (Mahnke and Leitner, 2009). Fig. 12 shows OPC UA which is used between the layers of the automation pyramid as the data exchange model and through its server the OPC UA client can communicate with the services and functionalities of these layers.

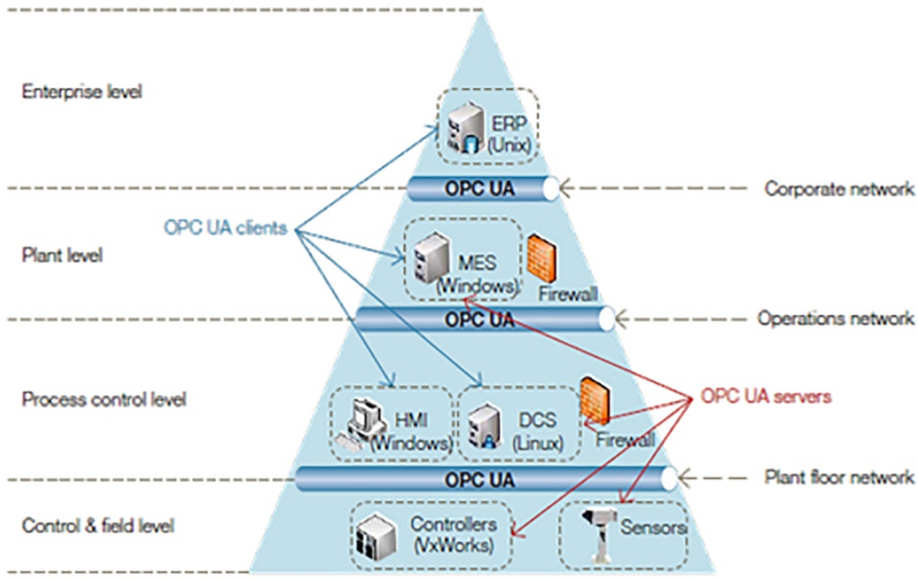

Figure 12. OPC UA effect on the process automation pyramid (Mahnke and Leitner, 2009)

5.3. OPC UA, the automation pyramid and cloud computing

Burke, 2015 refers to the influence of the cloud computing on the automation pyramid with an enabled OPC UA connection to the cloud space. Fig. 13 shows that each layer of this pyramid can act as a client and communicate with the cloud server. The figure specifically illustrates the communication of PLC with the OPC UA Historic Data Server in the cloud on an even-driven basis. Therefore, in such a network devices and services can autonomously initiate communication with one another horizontally and vertically and call up their own specific calculation method or algorithm from the cloud base server.

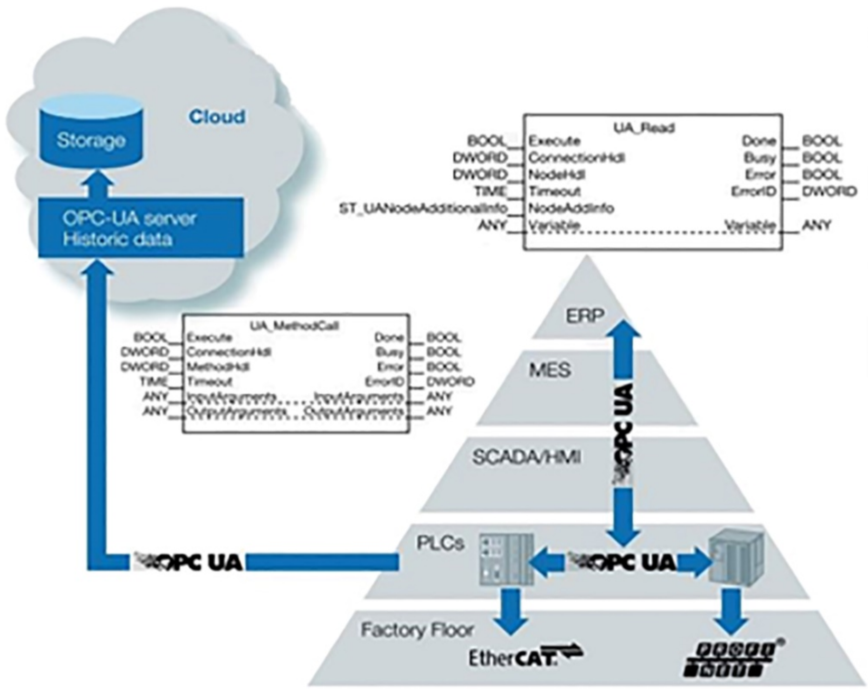

Figure 13. Implementation of OPC UA and cloud computing in automation with the PLC example (Burke, 2015)

Additionally, Fig. 13 emphasizes that in this semantic interoperability, without cloud server connection, PLCs exchange complex data structures with other controllers horizontally and call the control methods vertically from MES/ERP and retrieve new production orders via OPC UA communication protocol (Burke, 2015).

5.4. OPC vs. OPC UA

OPC UA unites different specifications of the classic OPC and provides a single entry point to offer data access, alarms and events. Unlike OPC, OPC UA has a single set of generic services to access the information by a very simple Meta model which only provides tags in its hierarchy and enables a very rich information model by using the object-oriented technique. This method collects information and applies them as the classic OPC (OPC DA Surrogate) in the graphics and in many other applications such as MES and ERP (Mahnke and Leitner, 2009).

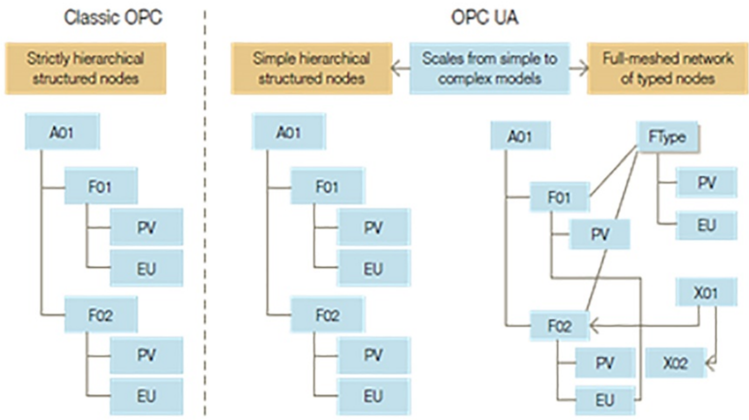

Figure 14. Classic OPC versus OPC UA models (Mahnke and Leitner, 2009)

OPC UA helps to integrate different data sets by rendering the semantics of the tags and eliminating the exchange of the tag lists (Mahnke and Leitner, 2009). Fig. 14 shows the difference of information modelling between the classic OPC and the OPC Unified Architecture. OPC uses strictly hierarchical and structured nodes while the OPC UA utilizes simple structured nodes and complex full meshed network of the typed nodes. Furthermore, the information model of OPC UA is described by an example of the typed nodes.

5.5. OPC UA information models

The communication standards of process automation include data semantics and Common Information Model (CIM). These standards focus on specific process or application, like IEC 61512 for batch processing, IEC 62264 at MES layer, IEC 61970 in energy management and IEC 61968 for energy distribution. However, OPC UA unifies the exchange of information models of CIM, metadata and the interoperability at the semantic level. OPC UA is also implemented as the support of other protocols and specifications like Field Device Integration (FDI), AutomationML, Device Integration, AutoID, BACnet (Building Automation), ISA-95, PLCOpen and Analyzer Device Integration (ADI) (Burke, 2015).

The OPC UA information model defines object types (e.g. ‘devices’) and variables (e.g. ‘String’). In this model, each high-order type is based on certain basic rules that enable the client to process complex information by knowing the basic rules without the need for understanding the relationships between them. Therefore, the clients navigate through the address space to read / write the data variables. Albeit, the foundation of the model is based on the nodes and references which are implemented as data tags for agile communicate throughout the model (Mahnke and Leitner, 2009). OPC UA specification provides various general types (as the parent type) and enables the child types which have the same properties as their parents, but the child type can possess its own extensions. For illustration, if a 'VesselType' is called, its reference can be called 'Diameter' of the vessel. Hence, if 'VesselType' is referred to the diameter of another vessel like a 'PressureVesselType' then the same reference (i.e. Diameter) is used (OPC UA, 2015a).

Fig. 15 shows the OPC UA information model which is divided into layers to meet a wide range of systems from PLCs to the enterprise level. The functionalities of these layers are (OPC-UA, 2015a):

Transport – for the data exchange mechanisms between the OPC UA applications with different transport protocols. It includes optimization in speed and throughput = UA TCP with UA Binary and firewall-friendly = HTTP + Soap.

Metadata model – to specify rules and basic components for publishing an information model via OPC UA including different nodes and types.

Base Services – to constitute the interfaces between a server (information provider) and clients (information user).

DA, AC, HA, and Prog stands for Data Access Live Data, Alarm & Condition, Historical Access and State machines, respectively. Additionally, the information model has a vendor-specific layer that can be developed and customized by the user.

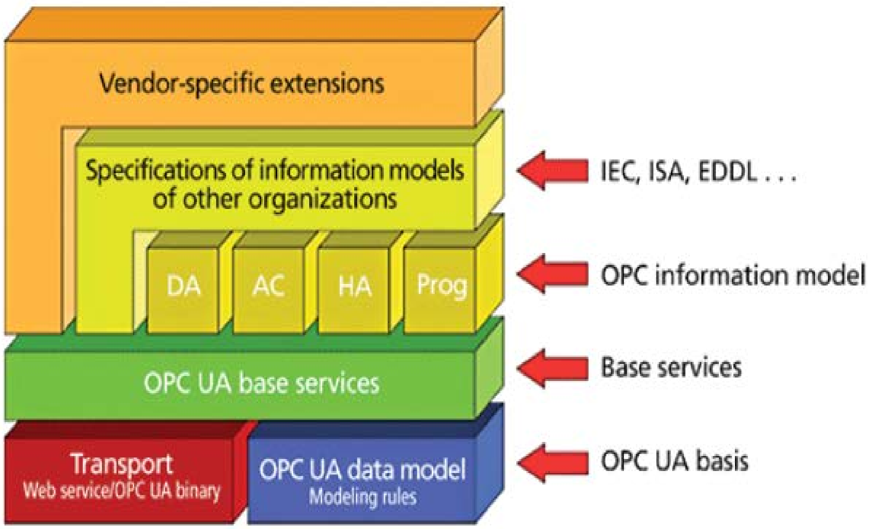

Figure 15. Information model layers for OPC UA (Thomas, 2013)

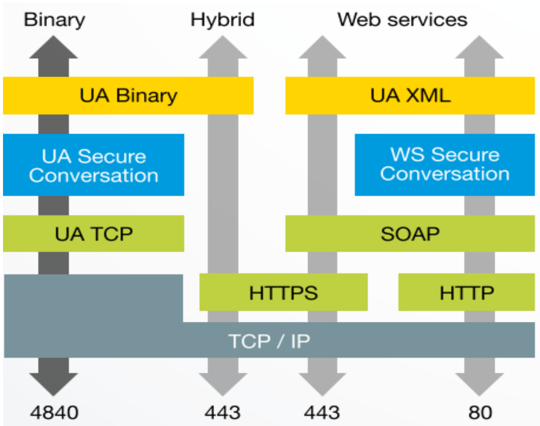

Figure 16. OPC UA transport profiles (Burke, 2015)

Fig. 16 details the transport layer of the OPC UA information model and categorizes the data transport into web services, hybrid and binary. The OPC UA transport profile shows the related communication protocol and defines data exchange mechanism between the OPC UA applications and the different transport protocols (e.g. HTTP through Web services via port IP 80).

5.6. OPC UA and ABB 800xA control system

ABB co. participated in the development of OPC UA specifications (e.g. Address Space, Information and Security Models) and has a special focus on OPC UA information modelling in order to fit well with the Extended Automation System 800xA and the Aspect Object Model. ABB also provides mapping concepts for integrating the 'third-party OPC UA servers' into the 800xA system to act as an 'OPC UA Client' (Mahnke and Leitner, 2009).

The OPC UA third party has C++ basis with the Software Development Kit (SDK) which provides ABB with the SharePoint server to collect the latest news and SDK updates. Moreover, ABB participated in the development of the ANSI C-based OPC UA stack to enable the real-time operation system in AC800M PLCs via VxWorks. Independent from ABB co., the OPC UA Foundation also provides the stack for Linux and Windows operating systems (Mahnke and Leitner, 2009).

5.7. OPC UA security model

OPC UA has built-in security features (OPC-UA, 2015a) with a solid and scalable model which is based on detailed analysis of threats to address the authentication of the client / server, the integrity and confidentiality of the exchanged messages and the verifiability of the functional profiles. OPC UA also applies the security of the web-enabled platforms to secure the end to end communications between the nodes (Burke, 2015).

Fig. 17 shows the architecture of the OPC UA security at three levels which includes User Security, Application Security and Transport Security. At the user level, the mechanisms are executed once a session is set up and the client transmits an encrypted 'security token' to identify the user for the server. Next, the server will provide the authorization access to the object in the server. At the application level, the security is a part of the session set-up and includes the exchange of the digital signed certificates. At this level, the software certificates identify the client / server and the OPC UA profiles to describe the capabilities of the server. Transport level security provides the integrity (by signing the messages) and confidentiality via encryption of the messages. This method prevents the disclosure of the exchanged information and ensures the intactness of messages (Burke, 2015).

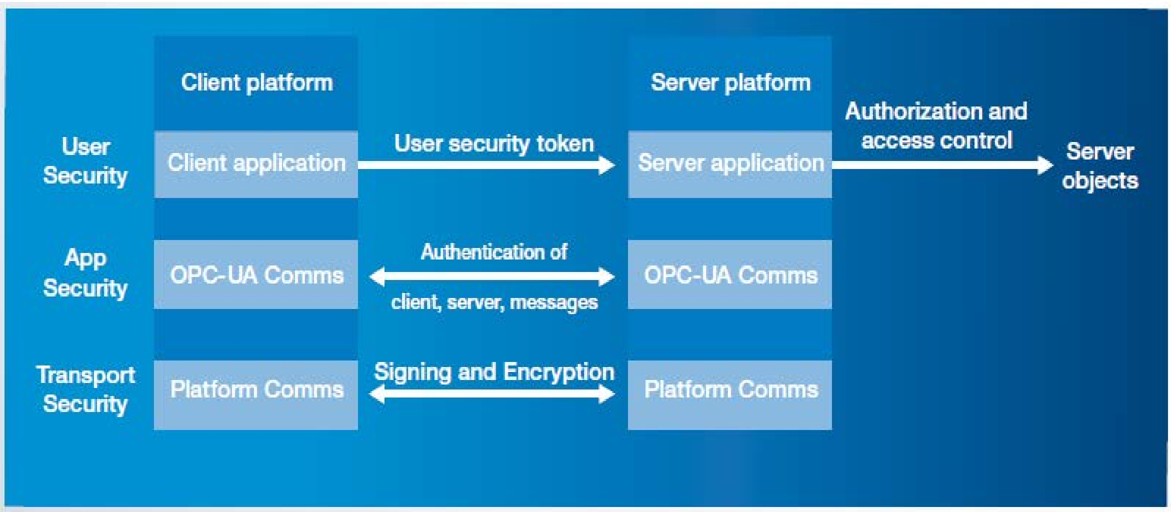

Figure 17. Scalable level security concept in OPC UA (Burke, 2015)

OPC UA adjusts the security level in the different end points at the same time and even defines nodes without security or the so-called 'No Security Profile'. The scalable security level in OPC UA enables the system operator (administrator) to decide the place and the time of the security application and to deactivate or to active a certain end point. (Burke, 2015). Moreover, the security policy defines the algorithms for encrypting the communication messages with three options such as ‘None’, ‘Sign’ and ‘Sign & Encrypt’. The way of encryption is described by the Security Mode which itself is defined by the Secure Channel. The OPC UA security mechanisms are realized as a part of the OPC UA stacks which is included in the software package (Burke, 2015).

OPC UA security was analyzed by the Federal Office for Information Security (German Government BSI) (OPC-UA, 2015a) and by Jens Wiesner, Head of Division C12, BSI who quoted “No crush could be generated during many tests of the communication stack” (Burke, 2015).

EXPERIMENTAL PART

In the experimental part, the modern process automation setup is designed, implemented and described. The thesis aims to connect three mini plants to ABB 800xA physically, to configure them in the ABB control system virtually and to connect the OPC UA server to its local client. Additionally, the OPC UA connection is tested with the mini plants measurements and variables to enable reading and writing data on the ABB 800xA control system through its local and remote clients.

The system is embedded in the 5G wireless network and facilitated with the cloud space for data analytics and cloud computing, but they are not the focus of this thesis. However, this thesis builds parts of an educational infrastructure for modern process automation to bring more flexibility in all aspects and layers of the old process automation hierarchy by the latest tools and technologies like OPC UA, Industrial Internet, Cloud Computing and 5G. This modern educational setup will help engineers and students to practice future process automation challenges and cope with the new emerged trends like Cyber Physical System (CPS), System of Systems (SoS), the Factory of the Future (FoF) and Big Data. Better process optimization, less human error, increased safety and security, less cabling and efficient business models are only some of the outcomes of this modern process automation setup.

The first part of the experimental part starts with the state of the art of architecture and follows with a brief description of its elements. The second part describes each equipment connection with their virtual connection to ABB System 800xA. Moreover, the local server and the client of the OPC UA are configured and explained after the equipment part. Finally, the conclusion and future prospectives are discussed.

6. Overall Architecture of the Factory of the Future

The modern process automation teaching environment is built around the process automation architecture for the Factory of the Future (FoF). It consists of five sections, including ABB System 800xA with its PLCs connected to the sensors and actuators of the mini plants, the cloud space with web frameworks, 5G wireless connectivity station, monitoring stations (local and remote) and OPC UA as the standard infrastructure for the exchange of the process control data. Fig. 18 shows the state of the art of the architecture, the Factory of the Future.

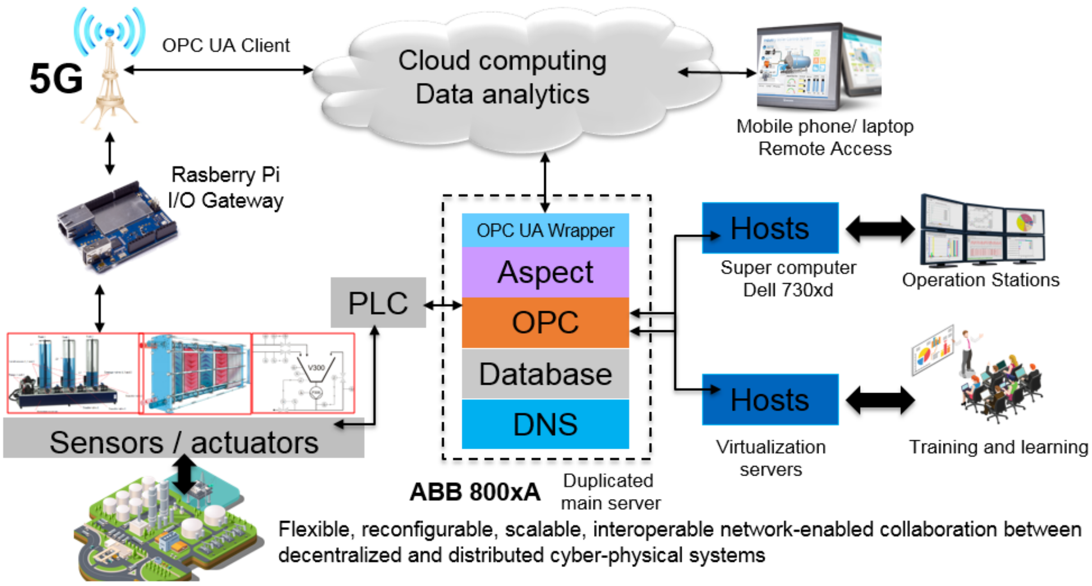

Figure 18. Architecture of the Factory of the Future

At the bottom of this architecture, the three mini plants with their sensors and actuators are wired to the PLCs of the ABB I/O cabinets physically and they are connected to the ABB network with Ethernet cable. The duplicated servers of the ABB 800xA handle servers including Aspect, Connectivity, Application and Domain. Super computer Dell 730xd servers (Hosts) include the Play and Spark frameworks as well as the configuration and the operator stations of the setup. Moreover, the cloud space is a cluster of services including scalable computation, data storage and data analytics that can be accessed through the Transmission Control Protocol (TCP) and Internet Protocols (IP).

Fig. 19 shows the relation of the frameworks and the cloud space. In this architecture, the data analytic algorithms are encoded with the Spark Core, which include time series, SQL and streaming. Building Spark inside the Play framework enables a play - spark module with the Java and Scala programming language. These two frameworks can access ABB 800xA via OPC UA wrapper for data collection, either from the local (ABB Duplicated Servers) or cloud databases.

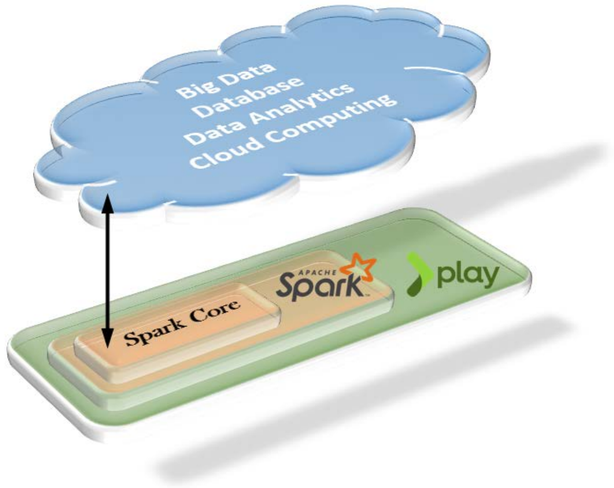

Figure 19. Cloud Services with the Spark and Play Framework

The other important part of this architecture is the implementation of the 5G wireless network prototype. The 5th generation network provides this architecture with the higher transfer rate and density of the communicating devices. This cellular base station with its own antenna enables wireless and real-time data collection from the distributed sensors and the actuators of the mini plants. The collected data via the 5G testbednetwork can be sent to the cloud space or any mini computer (e.g. Raspberry Pi®) that can communicate with the ABB duplicated servers. Therefore, the mini-computers can manipulate the bottom level of this architecture (i.e. mini plants) via the accessed PLCs in the ABB network.

OPC UA is another bold feature of the architecture that its relation and cooperation with ABB 800xA were indicated in the literature review part. In addition, the OPC UA wrapper makes the old OPC DA surrogate visible and accessible through the whole architecture and more specific for the cloud services. The wrapper exposes the COM OPC server as a folder in the OPC UA server address space, which can be accessed by the cloud client.

As any automated process needs monitoring, four operation stations and 24 additional computers clients are configured and connected to the setup for teaching and research purposes. Additionally, the system can be accessed remotely through the cloud space with its connection to the ABB network. This network is a part of Aalto local network and secured with Aalto network security. At the data communication level, the security follows the OPC and the OPC UA protocols that were described in the literature review. The following part describes the architecture elements briefly.

6.1. ABB system 800xA

The Industrial^{IT} Extended Automation System 800xA is a comprehensive process automation system. It covers operation and configuration of the continuous and batch control applications with the unique integration principles based on the Aspect Object technology that can integrate information like live video, documentation (using word), quality analysis, and maintenance information (for example from SAP or Maximo). ABB 800xA follows OSI model with the standard hardware, operating system and protocols that allow the data to be obtained not only from the ABB systems, but from a variety of sources. The sources include Windows 2003 / XP, internet explorer, visual basic, ActiveX Controls, OPC-OLE for process control, Microsoft Component Object Model (COM), PROFIBUS and Fieldbus Foundation (ABB Support Group, 2004).

The Aspect Object™ architecture is a cornerstone of the Industrial^{IT} 800xA concept. The Aspect Objects refers to the objects of the real process equipment or entities, which can be a physical process equipment (e.g. a valve or a mini plant). ABB 800xA emphasizes *Domain Name Server* (DNS) to handle configuration of the users and security in the Windows and *Database Server* to support historical array and data collection for information management. In addition, the *OPC Server* handles the conversion of the hardware communication protocol from PLC to the OPC protocols and *Aspect Server* provides static data like graphical elements, libraries and objects. Finally, the *OPC UA Wrapper Server* handles the communication of the classic OPC server with other entities (ABB Support, 2004). It is noteworthy that the functionality of the servers is beyond what is mentioned here.

Engineering Workplace/Plant Explorer and *Control Builder M Professional* are the two main tools of the ABB System 800xA and used in this thesis to design and configure the mini plants in the ABB control system. The *Engineering Workplace* enables the design and management of the Aspect Objects and their related modules. The workplace handles the complete lifecycle of the process automation projects, but this thesis utilizes this tool only to design the Human Machine Interface (HMI) of the mini plants. Students and researchers navigate through the interfaces of different projects with choosing the right structure of this tool. Some of the important structures are function, control, aspect, and graphics. The *Control Builder M Professional* is another tool for configuring and maintaining control objects. This tool handles PLC programming, IPs and the configuration of the physical connections of the mini plants in 800xA.

ABB 800xA safety follows IEC 61508 and IEC 61511 compliant Safety Instrumentation System (SIS) that spans from the Safety Integrity Level (SIL) to I/O modules and controllers.

6.2. PLCs and the sensors/ actuators

The backbone of the operation is the Programmable Logic Controllers (PLCs). ABB 800xA provides five PLC programing languages for the user, such as Function Block Diagram (FBD), Structured Text (ST), Sequential Function Charts (SFC), Instruction List (IL) and Ladder Diagram (LD). The PLC controllers of this modern setup consist of the PLC CPUs and I/O cards that are placed in the ABB I/O cabinet. The system description part describes the cabinets and their physical connections in more detail.

6.3. Cloud space

Cloud is one of the emerging technologies promising a wide range of application for various Internet Technology users and brings the Internet of Services (IoS) paradigm to the real world together with business technologies and Big Data analytics (Wahlster *et al.*, 2014). Data center hosting (cloud database) and utility computing (cloud computing) are the most relevant applications of the cloud technology to the architecture of this thesis (Winans and Brown, 2009). In the architecture, the cloud is the enabler of data clustering, elastic computational power and other future industrial application. Moreover, the cloud features the possibility of unlimited database capacity for data analytics in real-time, either from the mini plants or importing Big Data from an external source. The following part briefly describes the cloud computing architecture and its application. (Chui *et al.*, 2013).

The National Institute of Standards and Technology (NIST) defined cloud computing as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g. networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." (Snaith, Hardy and Walker, 2011). It has five characteristics, three models for its services and four deployment models. The characteristics are on-demand self-service, broad & ubiquitous, resource pooling, rapid elasticity, measured service and cloud security for multi tenancy (Ali, Khan and Vasilakos, 2015). Service models are Software-as-a-Service (SaaS), Platform-as-a-Service (PaaS), Infrastructure-as-a-Service (IaaS) and Anything-as-a-Service (XaaS) (Hoefer and Karagiannis, 2010). Could computing can be deployed in private, public, community, hybrid and virtual private (Archer *et al.*, 2011).

Moreover, cloud computing architecture can be divided into several layers, such as hardware layer, infrastructure layer, platform layer and the application layer. Fig. 20 shows the architecture of cloud computing (Rimal, Choi and Lumb, 2009).

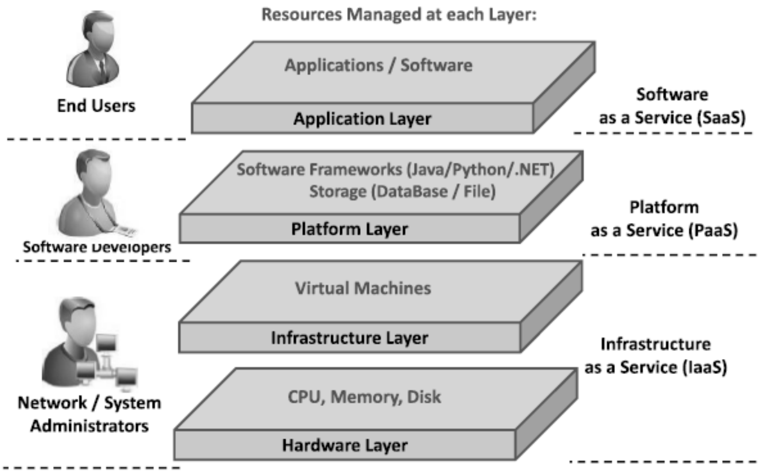

Figure 20. Cloud computing (CC) architecture (Zhang, Cheng and Boutaba, 2010)

In the architecture, the *hardware layer* handles the physical resources including hardware, network devices, configuration, fault-tolerance and traffic management. The *infrastructure layer* or the so-called virtualization layer provides a pool of computing resources and disk storages. The *platform layer* covers operating systems and application frameworks. This layer minimizes the development efforts by providing the platform for the developers as a service without installing any software or framework on their local computers. The *application layer* offers the cloud applications to the end users as a service. These applications are automatically scaled with high performance and low maintenance costs comparing with the traditional applications (Zhang, Cheng and Boutaba, 2010).

6.4. Play web framework

Play Web Framework™ is run in the cloud space for the advanced control algorithms and data analytics of process control application. Unlike pure Java frameworks, the Play is a Java and Scala open source service with a web application framework that provides the development of new applications by integrating the components with APIs. This framework is based on lightweight, stateless and web-friendly architecture. Other advantages of the Play over the pure Java Framework are asynchronous I/O (using JBoss Netty as its web server), integrated unit testing and modular architecture.

Play follows the Model View Controller (MVC) architecture and applies to web architecture for implementing user interfaces. Each application has three layers: Model, View and Controller layers. Additionally, the Play application defines these layers into its app directory as App/Model, App/Views and App/Controller. Fig. 21 shows these layers of communications when confronting an HTTP request.

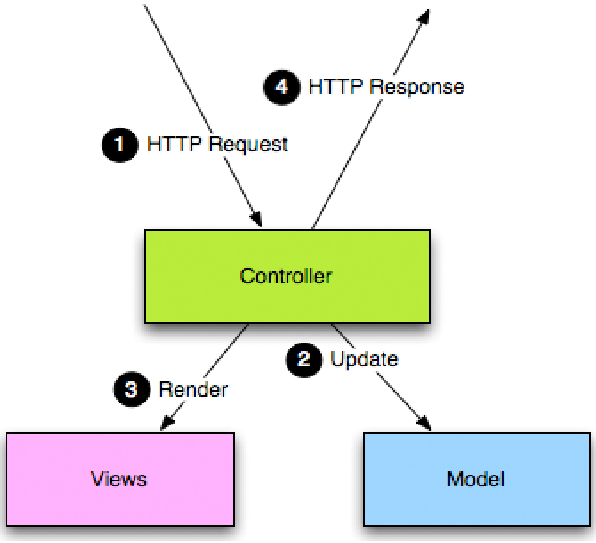

Figure 21. Three layers of the MVC application model for the Play framework (Play Framework, 2015)

6.4.1 The request life cycle in Play architecture

The framework is fully stateless and only request/response oriented where all the HTTP requests follow a single path. The framework receives this HTTP and the router tries to find the most specific route able to accept this request. Next, the corresponding action method is invoked by the application code which is executed and if a complex view needs to be generated, a template file is rendered. Then, the result of the action is written as an HTTP response. Fig. 22 shows the HTTP request path base on the MVC architecture.

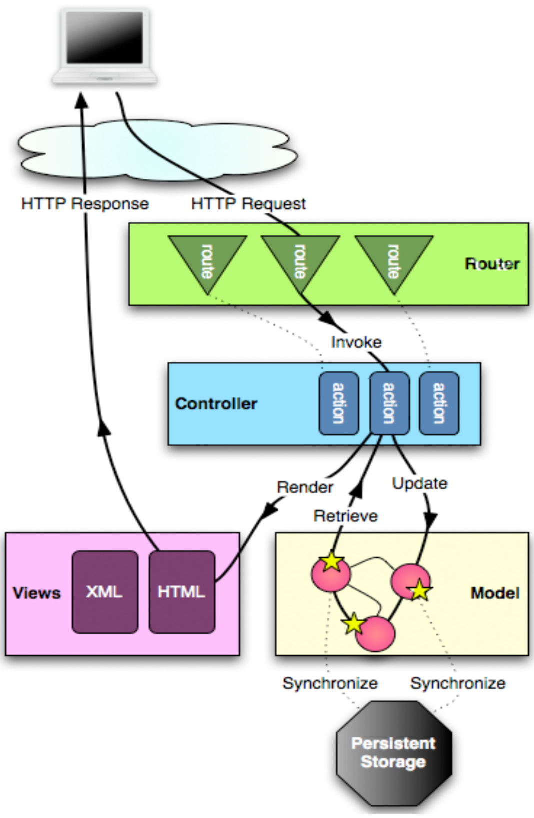

Figure 22. HTTP request path based on the MVC architecture pattern (Play Framework, 2015)

6.5. Apache spark framework

Apache Spark Framework™ is a fast and general engine for large scale data processing. This framework is an open source cluster computing framework, which provides the programmers with an application interface (for Java, Python and Scala). The interface is centered on a data structure called Resilient Distributed Dataset (RDD) and a read-only multiset of the data items which are distributed over a cluster of machines (Zaharia *et al.*, 2010). The framework is 100x faster than its equal frameworks from Hadoop MapReduce in memory and 10x faster on disk. Moreover, the framework can be run on Hadoop, Mesos, Standalone, or in the cloud with the access to diverse data sources. Spark core is the foundation of the Overall Projects concept which provides the distributed task dispatching, scheduling and basic I/O functionalities (ApacheSpark, 2017, p. 2).

Furthermore, the *Spark SQL* introduces a data abstraction called Data Frames, which provides the support for structured and semi structured data. The Spark SQL also provides a domain specific language (DSL) to manipulate the Data Frames in Scala, Java, or Python. It also provides SQL language support, with command line interfaces and ODBC/JDBC servers.

Spark Streaming leverages scheduling the capability of spark core to perform streaming massive analytics by ingesting data in mini batches and performing RDD transformation on each one of them. This technique facilitates the implementation of the Lambda architecture which is a data-processing architecture for massive quantities of data (PLURALSIGHT, 2016, p. 1; CloudEra, 2014, p. 1). However, this convenience comes with the penalty of latency equal to the mini batch duration and slows down the calculations and responses. Beside Spark, other streaming data engines that process data event by event rather than in mini batches, include Storm and the streaming component of Flink (Chintapalli *et al.*, 2016).

Spark Time Series are Java libraries for analyzing large scale data sets and distributed as the Spark-ts packages. These libraries offer a set of abstractions for manipulating data sets that are similar to the packages provided by Pandas, MATLAB, and R's zoo (Time Series, 2016).

6.6. 5G wireless connectivity

5G is the fifth generation of wireless network which is proposed as the next telecommunication standard beyond the current 4G/IMT-advanced network (ITU, 2017). 5G connectivity enables the higher capacity and density of mobile broadband users and most importantly supports device to device communication with ultra reliable features (Vinet and Zhedanov, 2011). Moreover, 5G aims at lower latency and battery consumption which benefits the implementation of Internet of Things (Best, 2017). 5G connectivity in the architecture of the Factory of the Fututre provides the students and researchers with a wireless connection between the PLCs and the sensors / actuators of the mini plants. Therefore, cabling failure is eliminated and the measurements are available remotely and in real-time. Fig. 23 shows the prototype of the cellular 5G testbed station.

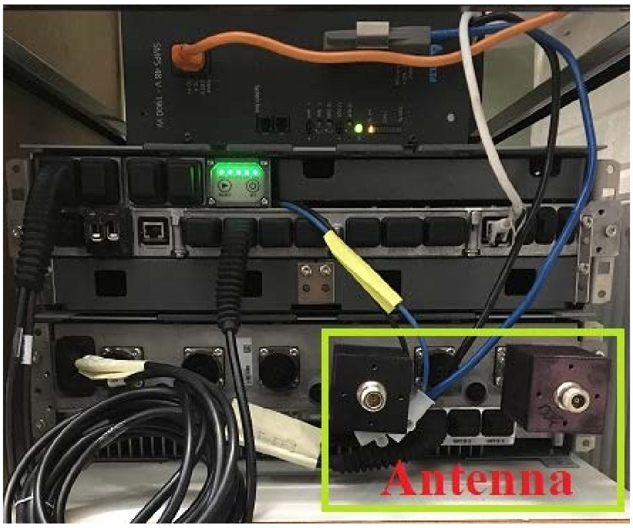

Figure 23. Base station of the 5G network prototype

7. System Description of the Modern Process Automation Setup

The setup is located in the A-Bio plant of Aalto University in Otaniemi campus and consists of three mini plants, I/O cabinets, ABB AC800M, computers and monitors. The equipment are connected to the ABB control system through ABB cabinets to pass the data from processes to the ABB network. Fig. 24 shows the overall mapping of the physical components of the setup. In the following part, the I/O cabinets are explained as the intermediate between the processes and ABB 800xA. Furthermore, each mini plant with their design, connections and configurations are described. Finally, the OPC UA wrapper is tested with the mixing tank example.

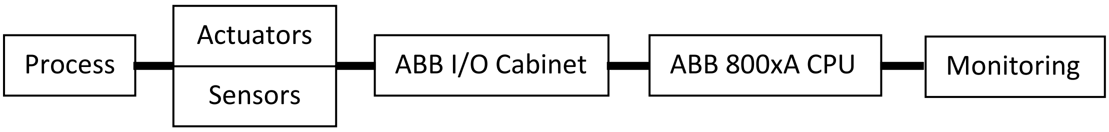

Figure 24. Overal mapping of the physical system

Fig. 25 presents the ABB I/O cabinet with the system tag ‘plant-CPU-cabinet PLC1.2’. In this cabinet, the cards are positioned in the right hand side and the lowest part is allocated for CPU, including PM856A (A1) with IP 172.16.08.xxx, CI871 (A2) with two input channels of 10/100M & 10M and the CI853 cards with two COMs (A3 & A4). Above the CPU, to the left, the power supply and fuses are designed to receive AC 100-240v and delivers DC 24-28v with 3-5-10A. On the top of the power supply, the protected switches from X1.11.4 to X1.11.8 are designated for connection to the cards. Table 4 presents the list of the cards and their specifications. The sensors and actuators are wired to these cards to communicate the analog / digital signals from the processes.

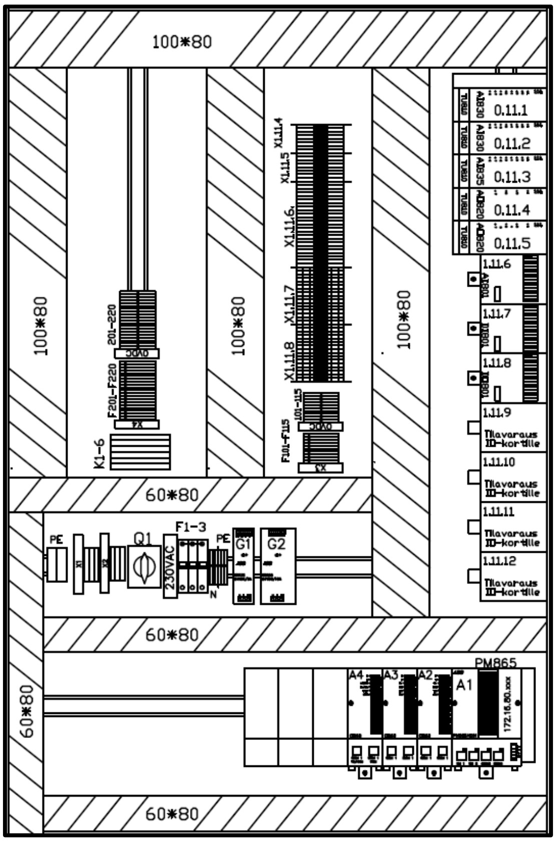

Figure 25. ABB I/O Cabinet 'CPU - cabinet PLC1.2'

Table 4. Cards used in ABB I/O cabinet

Card Tag	**Signal Type**	**Receive**	**Send**	**Voltage/Ampere**	**No. of Channel/ Channel Division**
AI830A	Analog	Analog Input (AI)		0VDC* – RTD*	8 Ch. /A^- B^+ C^+
AI835A	Analog	Analog Input		TC/mV	8 Ch. /A^- B^+ C^+
AO820	Analog		Analog Output (AO)	±10V/±20mA-Isol*	4 Ch. /B^+ C^+
AI820	Analog	Analog Input		±10V/±20mA-Diff*	16ch /A^- B^+ C^+
AO801	Analog		Analog Output	4 – 20 mA	8 Ch. / $+$ $-$
AI801	Analog	Analog Input		4 – 20 mA	8 Ch. / $+$ $-$
DI801	Digital	Digital Input (DI)		24 VDC	16 Ch. / $+$ $-$
DO801	Digital		Digital Output (DO)	24 VDC/0.5A	16 Ch. / $+$ $-$

*RTD: **Resistance Temperature Detectors /** *VDC: **Voltage with Direct Current /** *Diff: **Differential / *Iso:** Isolated

Active Cards:

- Multiple Heat Exchanger has AI830A, AI835A, AO820, AI801, and DO801
- Three – tank System has AO820, AI801, and DO801
- Mixing Tank System has AI820, AO801, AI801, DO801

In the following part, the connections of the multiple heat exchanger, the three-tank and the mixing tank systems are mapped. Each section contains Piping and Instrumentation Diagram (P&ID) and Human-Machine Interface (HMI).

7.1. Equipment: the multiple heat exchanger

Heat exchangers are widely applied to different industries with the concept of transferring heat from one medium to another. *Shell & tube* heat exchanger consists of a bundle of tubes inside a tube shell. *Double pipe* heat exchangers are used for dirty fluids with high viscosity (e.g. crude oil) and they are the simplest type of shell & tube. *Plate* heat exchanger is composed of many thin, slightly separated plates that have a very large surface area for exchanging heat. This type occupies small area and is used for low to medium pressure fluid with low viscosity. *Coil* heat exchangers are usually used for heating fluids at the bottom of tanks or other similar equipment and can be used with any fluid, but the heating medium which runs inside the coil needs to be clean and non corrosive.

In this part, the connections of the multiple heat exchanger system with four types of parallel heat exchangers are explained. The system consists of the shell & tube, a double pipe, a plate, and coil heat exchangers with 17 temperature sensors and two flow meters to measure the flow rate of hot and cold water inputs. Two globe valves are designed to adjust the input flow rates. Four pneumatic (ON and OFF) valves work in pairs to provide the system with cocurrent or countercurrent mechanism which are further explained in the description of the process. Eight manual ball valves control the inputs (hot and cold water) of each heat exchanger and provide the chance of studying some specific heat exchangers or a single heat exchanger. Since this mini plant has different heat exchanger types and they are paralleled to each other, different fluid types with different pressure can be studied. Table 5 shows all equipment tags of the heat exchanger system.

Table 5. Equipment tags of the multiple heat exchanger

Equipment	System/ P&ID Tag	Specification	Card in ABB Cabinet/ Active Channel
Shell & Tube H.Ex.*	EA-101	-	-
Double Pipe H.Ex.	EA-104	-	-
Plate H.Ex.	EA-103	-	-
Coil H.Ex.	EA-102	-	-
Hot Input Valve	VFIC-1	Pneumatic Actuator/ Globe Valve/ Analog Signal	AO820/ Ch. 1
Cold Input Valve	VFIC-0	Pneumatic Actuator/ Globe Valve/ Analog Signal	AO820/ Ch. 2
Flowmeter A	FlowM-A	Electromagnetic Type/ 100-1000 l/h / Analog Signal	AI801/ Ch. 1
Flowmeter B	FlowM-B	Electromagnetic Type/ 100-1000 l/h / Analog Signal	AI801/ Ch. 2
Control Valve	V-101/ V-102 V-103/ V-104	Pneumatic Actuator/ Ball Valve/ Digital Signal	DO801/ Ch. 7-10 on switch X1.118
Manual Valve	VA1 to VA8	Ball Valve/ Open-Close/ ISO PN100	-
Temperature Sensors	Temp1 to Temp17	Resistance Temperature Detector (RTD)/ Analog Signal	AI803A & AI835A/ Ch. 1-8
Cold Pipe Supply	25CW001* to 25CW017	DN 25	-
Hot Pipe Supply	20HW018 to 20HW026	DN 20	-
*Pipe Tag: Size(mm) + Flow + No. of pipe + Material of Pipe (unknown)			

As discussed earlier the sensors and actuators are connected to the ABB cabinet. However, the heat exchanger system has pneumatic actuators and since the ABB cabinet is only providing analog / digital signals, another cabinet is designed to convert these signals to pneumatic references. The cabinet tag is ‘F38340 DetaLab Cabinet’ which passes some signals without any manipulation. Fig. 26 and Fig. 27 show the conversion cabinet and the modified system overview, respectively.

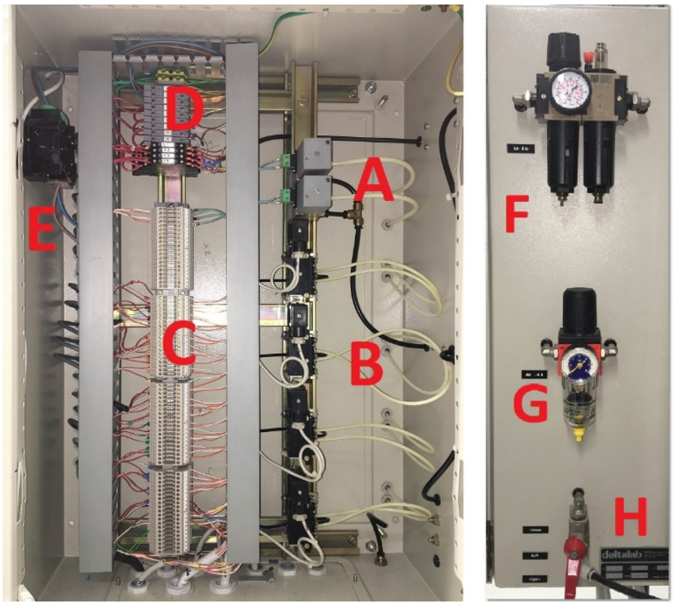

Figure 26. Conversion Cabinet F38340 DataLab

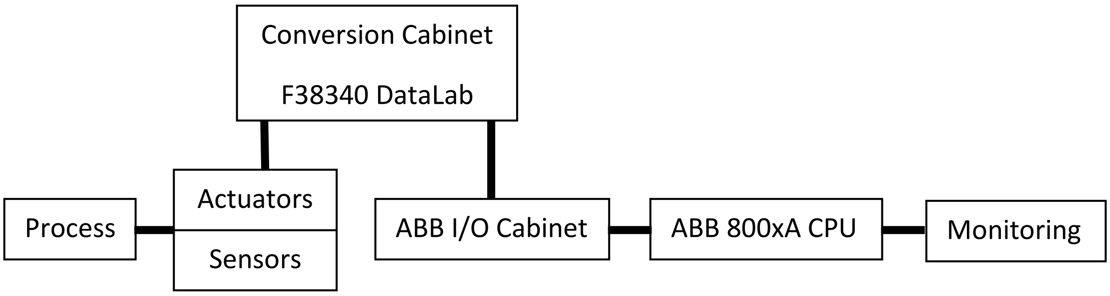

Figure 27. Modified overview of the multiple heat exchanger with the conversion cabinet

Table 6 presents different parts of the conversion cabinet which act as an intermediate cabinet between the ABB I/O cabinet and the system elements.

Table 6. Parts of the conversion cabinet

Conversion Cabinet Part	Name	Application	Coming from	Going to	Specification
Part A	VDO I/P Convertor	Converting ampere signal to pressure	Analog Signal from AO820	Pneumatic Actuators of valves VFIC_0 and VFIC_1	Input: 4-20 mA Output: 0.2-1 bar Direct
Part B	KUHNKE On/Off Convertor	Converting Voltage signal to Pressure on/off	Part D	Control Valves V-101 to V-104	220V 5VA
Part C	Switch	Passing Signals	17 temperature sensors	Analog Signals AI830A & AI835A	-

Part D	Switch	Passing Signals	Digital Signal DO801 to switch X1.118 Ch. 7-10	Part B	-
Part E	-	Power Supply	-	-	-
Part F	Pressure Indicator	-	-	-	Indication for valves VFIC_0 & VFIC_1
Part G	Pressure Indicator	-	-	-	Indication for valves V-101 to V-104
Part H	Pressure Supply Valve	Main Pressure Input	-	-	On/ Off

Between the ABB network and the conversion cabinets, the temperature signals are transferred with the cable 1, 2 and 3. Four control valves and the flow meter signals are transferred with the cables 4 and 5. Moreover, the cable 6 is sending the flow meter signals to the ABB I/O cabinet.

Fig. 28 presents the P&ID of the heat exchanger system. In the mini plant, the hot (VFIC_1) and cold (VFIC_0) water flows through the two control valves. Different cold water arrangement provides the cocurrent and / or countercurrent option. Inside the ABB control project, this feature is simplified to the True and False mode. True for all the valves represents the cocurrent heat transfer mechanism and it means V-102 and V-104 are open and V-101 and V-103 are closed. The false mode reveres the valve positions to enable the countercurrent feature.

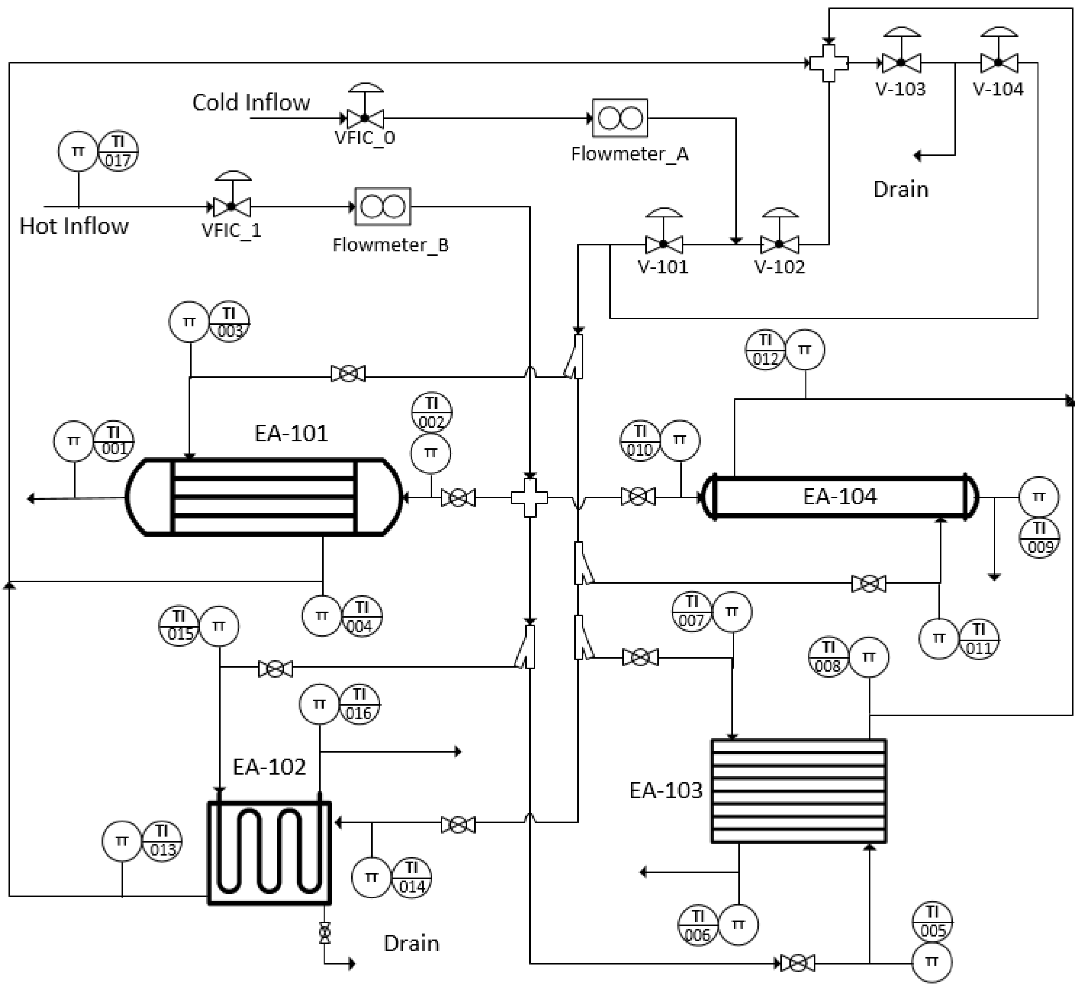

Figure 28. Multiple Heat Exchanger System P&ID

The virtual twin of the heat exchanger system is defined on the ABB engineering workstation and called ‘Heat_ExchangerSystem, site’. Controllers of this mini plant are defined in the Controller Builder M Professional under the project name ‘Heat_ExchangerSystem’.

Fig. 29 shows the equipment twin in ABB as the Human Machine Interface (HMI) that allows operators and students to have the overview of the system during operation and link all controlling actions to this interface. The interface is provided by the Aspect server and since the nodes of this server is combined with the Application and Connectivity servers, thus, the system accesses all objects and modules of the project from the HMI.

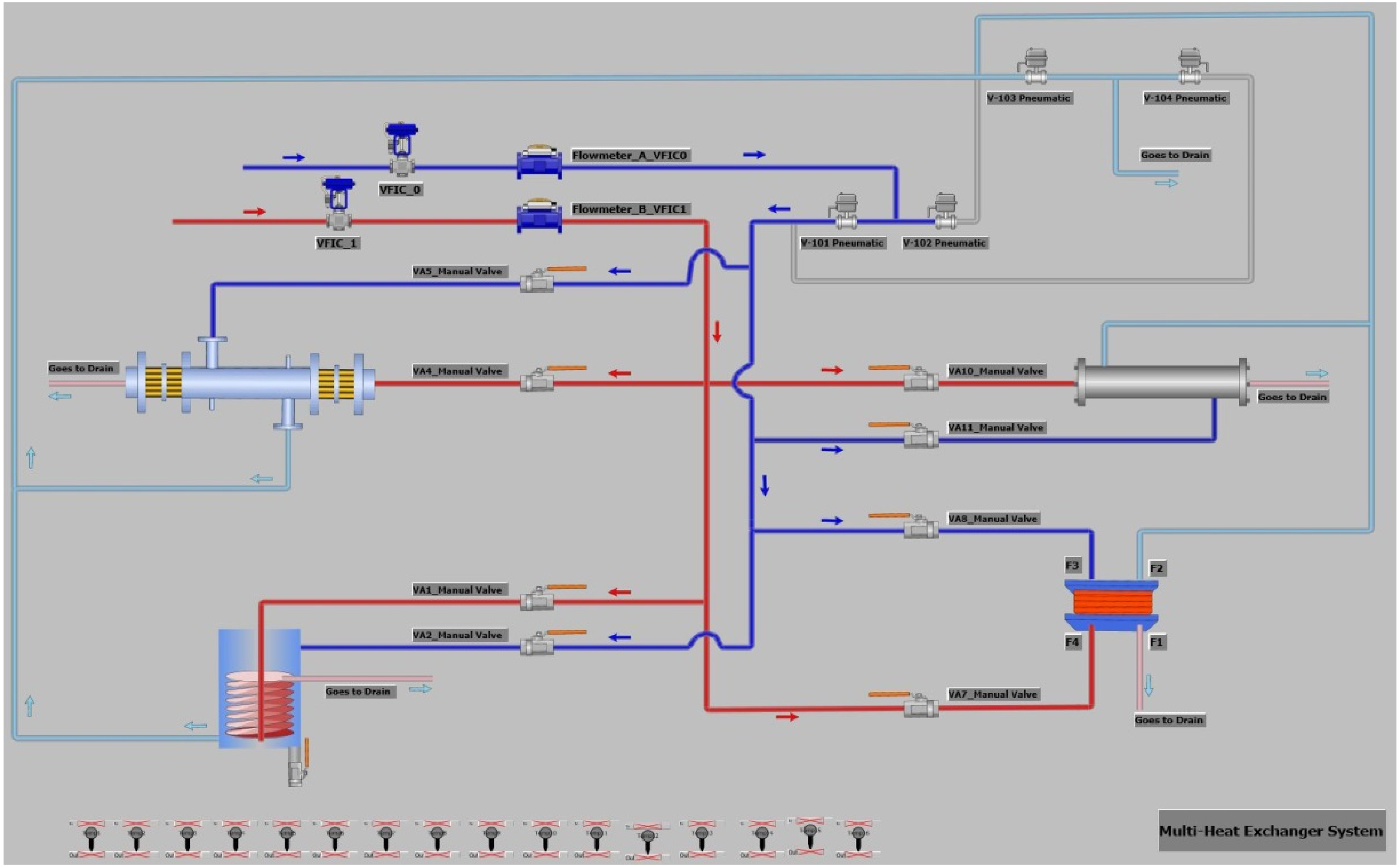

Figure 29. HMI or the user interface for heat exchanger system in ABB

Beside the virtualization of the equipment (HMI), all of the physical connections from the equipment to the cards need to be introduced to the ABB system. Fig. 30 shows the Control Builder M Professional and the active cards of the ModuleBus where the cards are synched with the ABB network and detected by the network automatically. Libraries of the ABB servers handle the communications with these cards.

Fig. 31 shows the configuration of the cards and their introduced variables which are defined under the ModuleBus section in the hardware AC 800M. Identical to the physical connections, the same number of the channels are available and detected by the ABB 800xA. Thus, each variable depending on the variable type, is configured in ABB on the same channel as its physical wire connection. Seventeen temperature measurements are connected to AI830 and AI835A. The cards AI801 and AO820 are communicating analog signals for the flow meters and the input valves respectively. The card DO801 sends the digital signals of the four digital valves to regulate the concurrent and countercurrent flows.

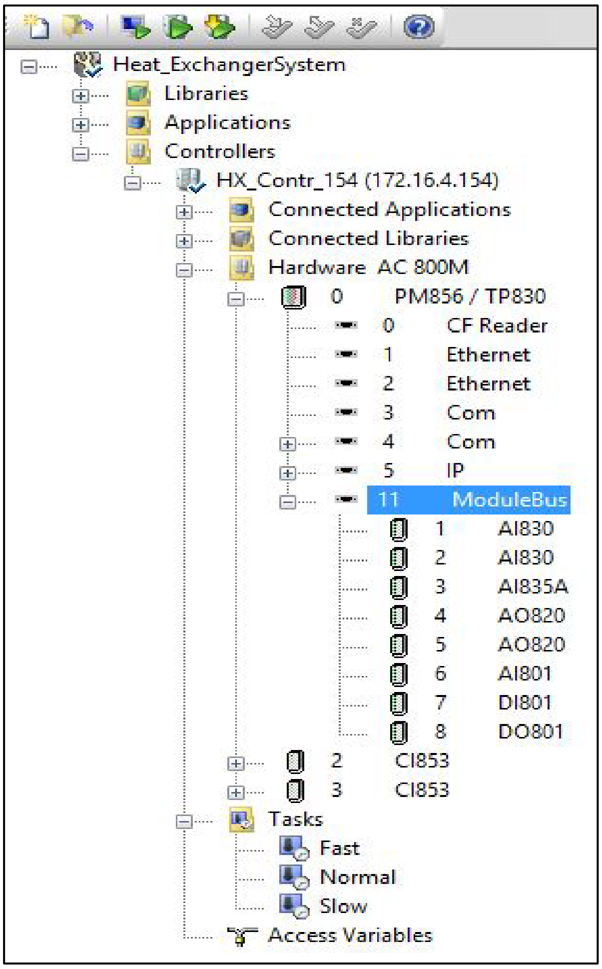

Figure 30. Heat exchanger system in the Control Builder of the ABB System 800xA

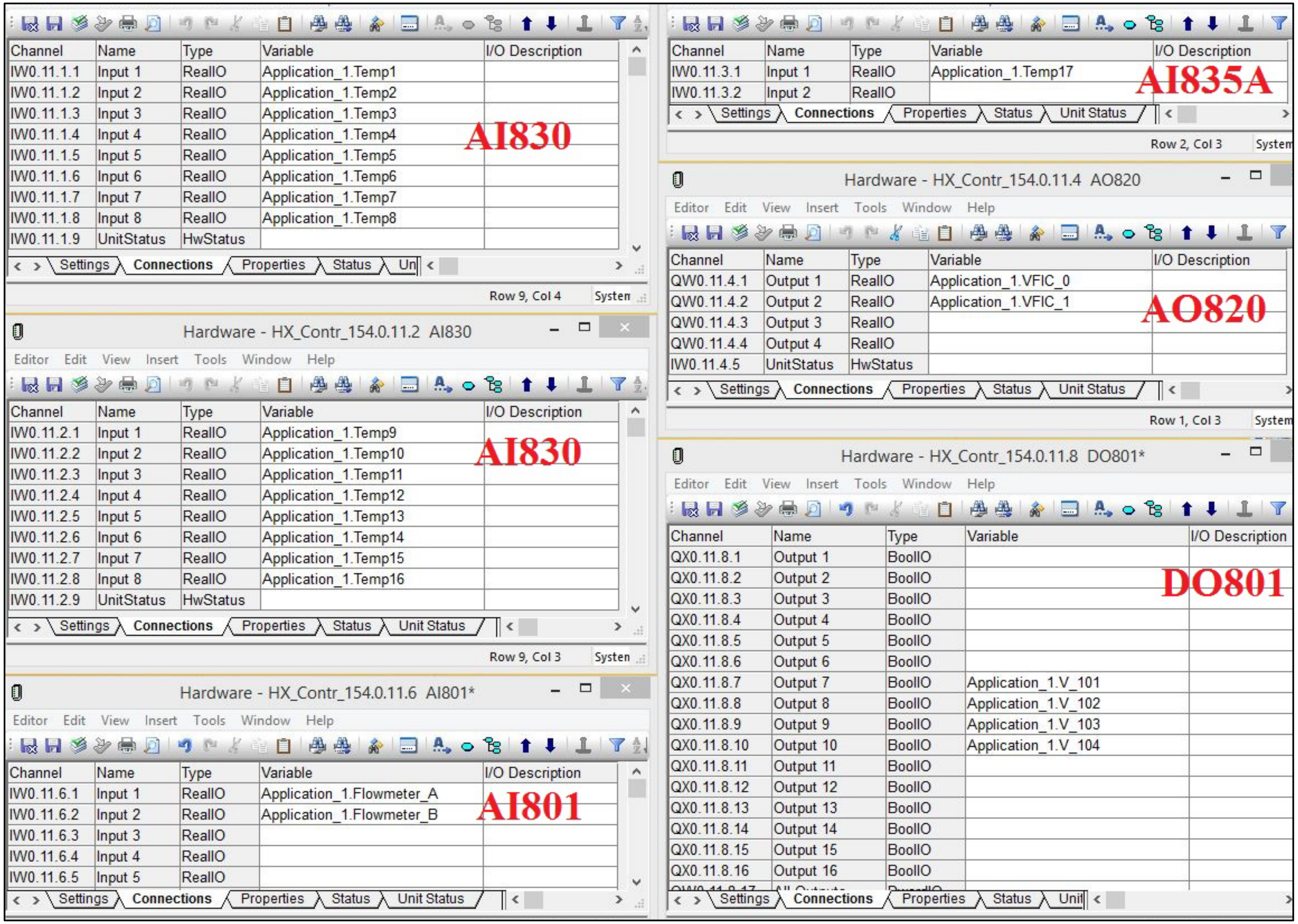

Figure 31. I/O Cards with the variables for the Heat_ExchangerSystem in the ABB control system

The communication between the cards, measurement signals and the controllers needs the connected libraries of the signal blocks. The signal blocks use the connected libraries, which are the ABB precompiled routines and modules to enable the communication between the ABB network servers and the equipment variables. The configuration of the mini plants follows the signal blocks of 'SignalInReal' and 'SignalInBool' where the variables of the heat exchanger system are connected as analog and digital, respectively. These blocks are categorized into valves, flow meters and temperatures. Fig. 32 shows the defined signal blocks under the Applications module with a fast mode controller. In the figure, 'V_10x', 'Tempx', 'VFIC_x' and 'Flowmeter_x' represent the variables of the pneumatic valves, temperature measurements, input water and the flow meters.

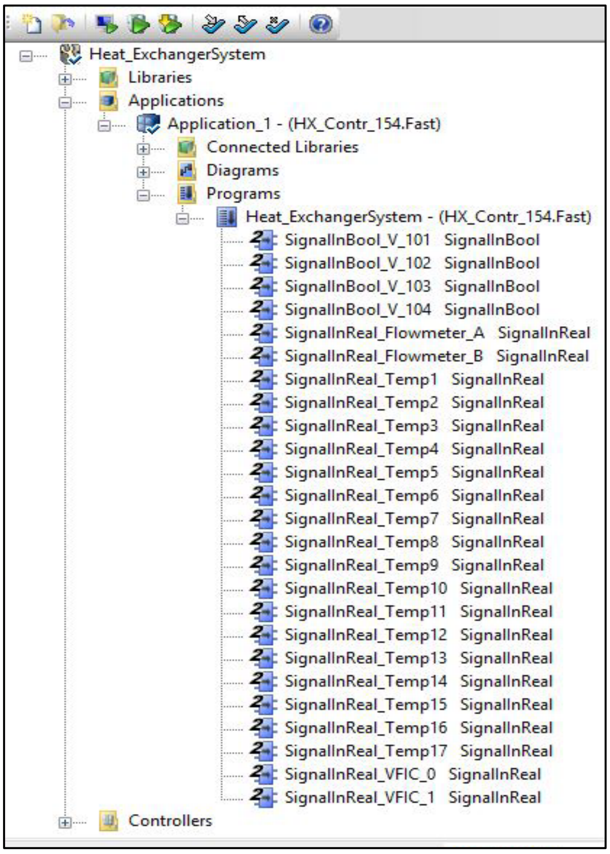

Figure 32. Connected signal blocks of the Heat_ExchangerSystem

7.2. Equipment: the three-tank system

The three tank system is the second mini plant of the setup that focuses on controlling levels of the tanks in series. Fluids are usually stored in cylinder tanks and their levels are affected by the level of the neighbouring tanks which causes nonlinear phenomenon. Investigation of the nonlinear multi variable feedback control and fault diagnosis of the three tank system is used as one of the popular experimental systems in the control laboratories (Hou, Xiong and Patton, 2005).

The system consists of the three cylinder tanks, one reservoir (main tank), six control valves, two pumps and the three level measurements. This chapter started with a general introduction to the ABB cabinet. However, for synchronizing of the three tank system to the ABB control system the original cabin is modified. Fig. 33 shows the overview of mapping this system.

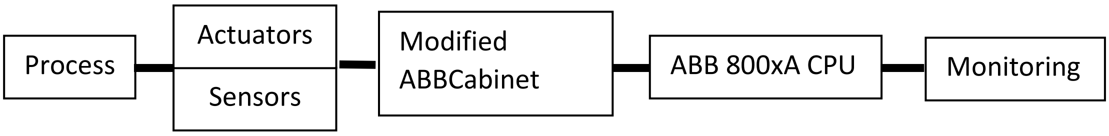

Figure 33. Overview of the three tank system with the modified I/O cabinet

The system has six digital valves with ON and OFF modes. Therefore, 12 Relays have been added to the cabin as the intermediate between the valves and their related cards (DO801). The Fig. 34 shows the SCHRACK Relays (RT78725) that specify the allocation of the two relays for each valve. The operators and students should be cautious that for each valve, the ON and OFF modes should not be run together, otherwise, the actuators are damaged.

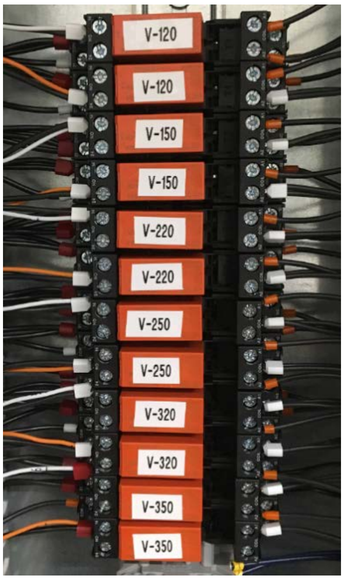

Figure 34. Added relays for 6 digital valves

Moreover, the two EPH invertors (GS24S Electronik) were placed between the I/O cards (AO820) and the pumps. However, the invertor connection was modified to match with the pump specifications as shown in Table 7.

Fig. 35 presents the electrical connection layout of the invertors. As the layout presents, the channel 1 and 2 receive the voltage from the adaptors to provide the invertors with power since they are electrically isolated. The channel 5 and 6 send out the needed signals for the pumps and the channel 8 receives the signal from the analog card (AO820).

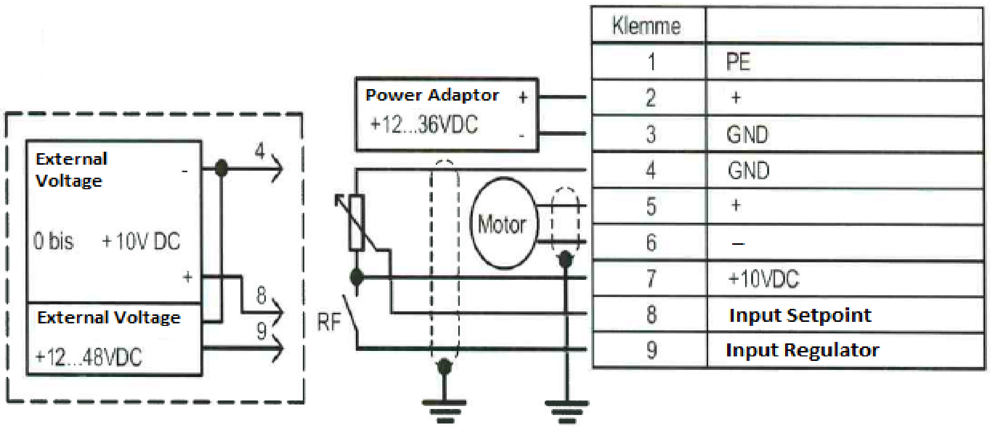

Figure 35. Three-tank electrical invertor connection layout

Table 7. Pump Invertors Connections

Channel	Description
1	-
2	+ Power from 12VDC Adaptor
3	- Power from 12VDC Adaptor
4	Ground (GND)
5	+ Output Signal to the Pumps
6	- Output Signal to the Pumps
7	+ 10 Volts Bridged to Ch. 9
8	0-10 Volts from the Card AO820
9	+ 10 Volts Bridged from Ch. 9

Fig. 36 shows the modified I/O cabinet and the pump invertors which are placed above PLCs. Table 8 presents the equipment tags, specifications and the related channel of the cards in the three tank system.

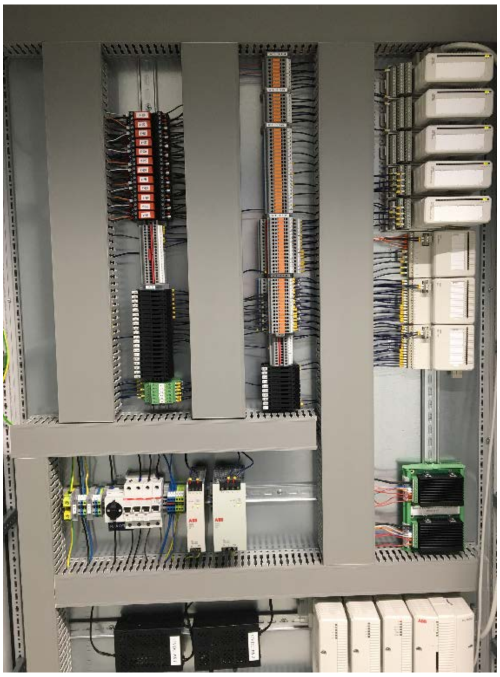

Figure 36. Modified I/O cabinet of the Three-tank system

Table 8. Equipment tags in the three-tank system

Equipment	**System/ P&ID Tag**	**Specification**	**Card in the ABB Cabinet/ Active Channel**
Identical Tanks	FA-100/ FA-200/ FA-300	Volume: 0.1 m^3/each Height: 0.63 m Diameter: 0.144 m	-
Main Reservoir	FA-104	Max Volume: 55 lit	-
Control Valves	V-120/320/220/350/250/150	Electrical Actuator, Digital Signal, +24V, 1A, signal ±10V, Operating time 10s	DO801 Ch. 5-16
Pump	GA-101/ GA-102	Analog Signal, 3-Chamber Diaphragm, 12 VDC*, 1.4 – 4.5 A Capacity: 7 lit/min	AO820 Ch. 1&2
Level Measurement	PLI-001/002/003	Analog Signal, Capacitive Pressure, 12-30 VDC, Output signal 4-14/ 4-20 mA	AI801 Ch. 1-3
Piping	6PF101PVC to 6PF116PVC*	Pipe: Tank Connecting Cross Sectional Area 0.5 cm^2	-

*VDC: **Voltage with Direct Current** Size(mm) + Flow + No. of pipe + Material of Pipe 6 (mm) + Process Flow (PF) + 101 + PVC

Fig. 37 shows the P&ID of the three tank system. In the system, GA-101 and GA-102 pump the water from the main reservoir (FA-000) to the FA-100 and FA-200 with adjustable flow rates (analog signal). Furthermore, the water level of the tanks are controlled with the adjusting valves and the pump flow rates in a feedback loop. The tank FA-100 and FA-300 have leaking and connecting valves that empty the tanks into the FA-000 and connect the tanks to the one next to, respectively. The tank FA-200 has a leaking and drain valves that are equipped with the digital actuators (digital signals). In addition, the pressure level measurement of each tank sends the level of the water back to the ABB card (AI801) with the analog signal.

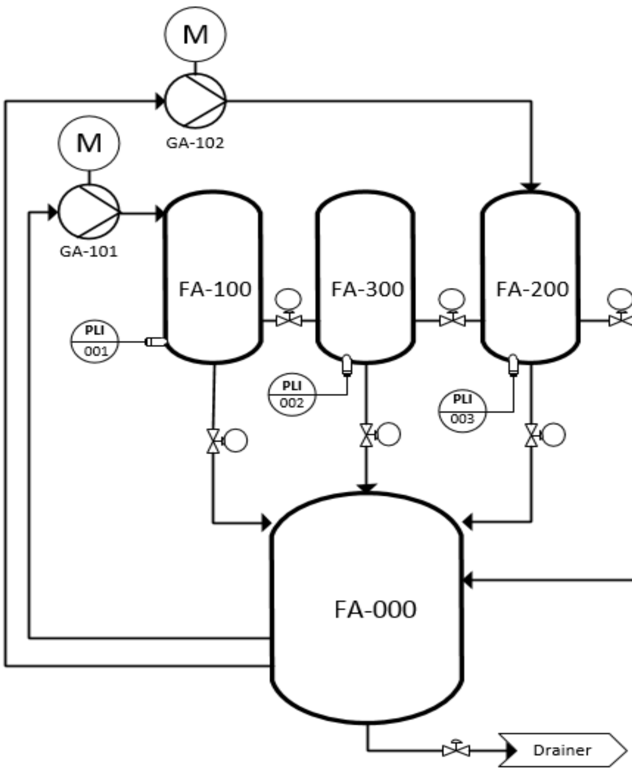

Figure 37. Three-tank System P&ID

Fig. 38 shows the designed and configured User Interface (UI) of the three tank system as the twin of the physical equipment in the ABB 800xA. The UI is implemented under the workplace with the project name ‘Three-tankSystem’. Similar to the heat exchanger system this UI can also access all features provided by the Aspect server which include trending and diagrams. The UI provides the predefined variables as an icon linked to the object. For example, the valve button ON in the UI is connected to its related signal block in the controller module.

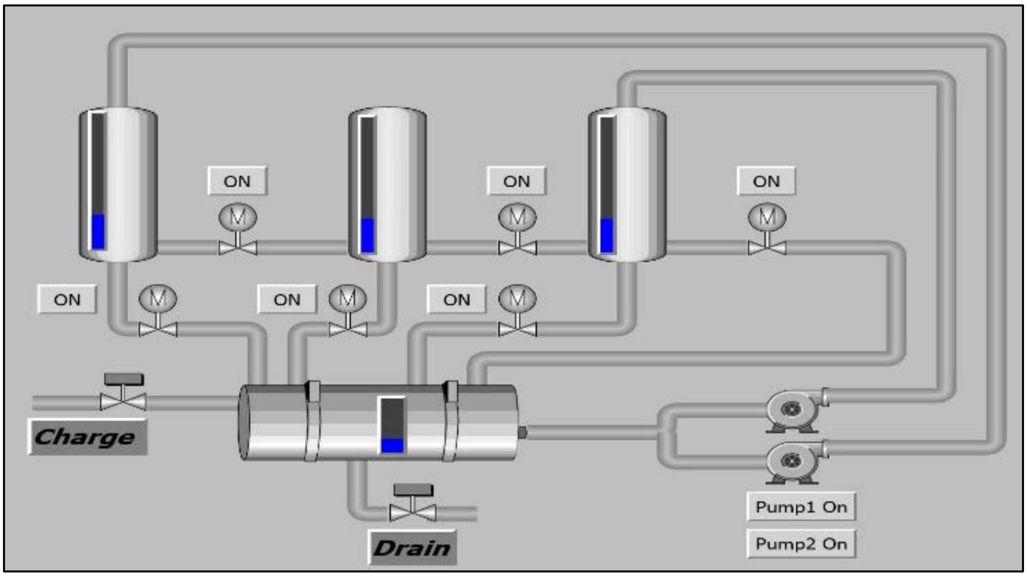

Figure 38. Human machine interface of the three tank system

The physical connections to the cards of the ABB cabinet need to be introduced to the system. Fig. 39 shows the Control Builder M Professional with the IP address 172.16.4.155 which is configured in the Connectivity server of the ABB 800xA and it has libraries, applications and controllers. The ‘Controllers’ section defines the cards, physical connections and the desired speed of performances to run the tasks in Fast, Normal or Slow mode. ‘Libraries’ has the precompiled routines and modules that enable the communication between the system elements while the ‘Applications’ provides the users with features for PLC programing and diagrams.

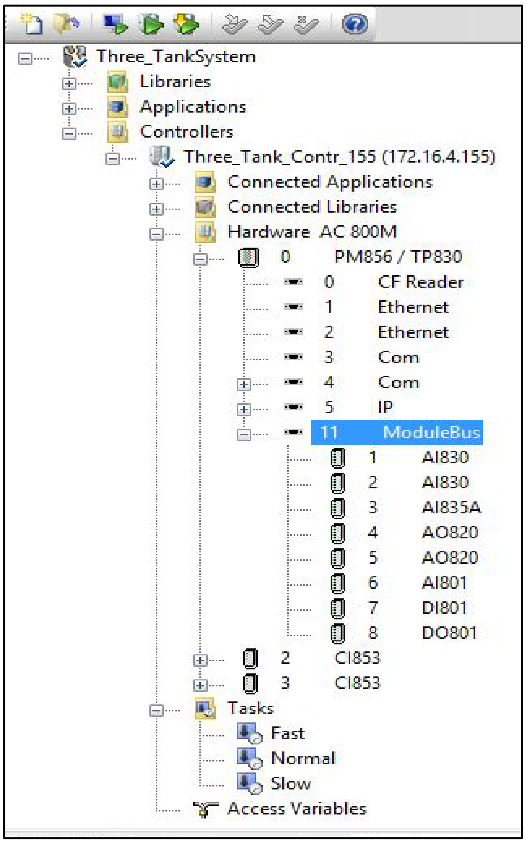

Figure 39. ModuleBus of the Three-tank System in the Controller Builder

Fig. 40 shows the active cards in the three tank system with the defined variables in the ModuleBus section. The card DO801 shows twelve occupied channels for ON and OFF modes of the six digital valves. The AO820 is an analog output card that sends the analog signal to the pumps while AI801 receives analog inputs form level measurements and indicates the level of each tank. Similar to the heat exchanger system, the signal blocks are defined so that the system can read the signals and connect them to its Real or Boolean variable in the UI. Fig. 41 presents the blocks for each signal in SignalInReal or SignalInBool.

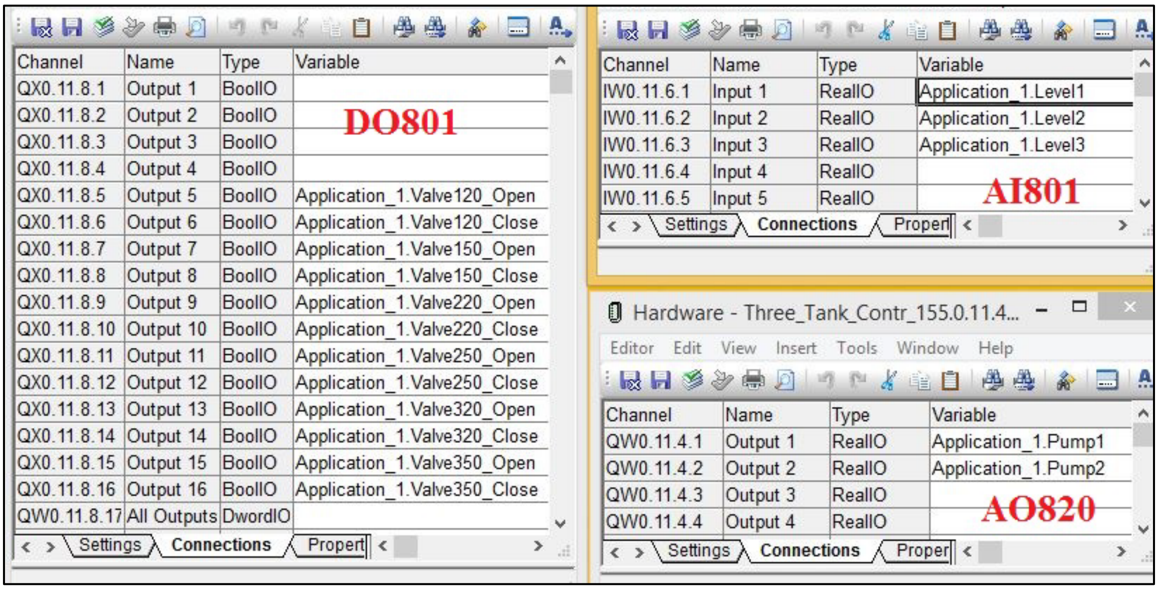

Figure 40. I/O cards with the variables for the three tank system in the ABB control system

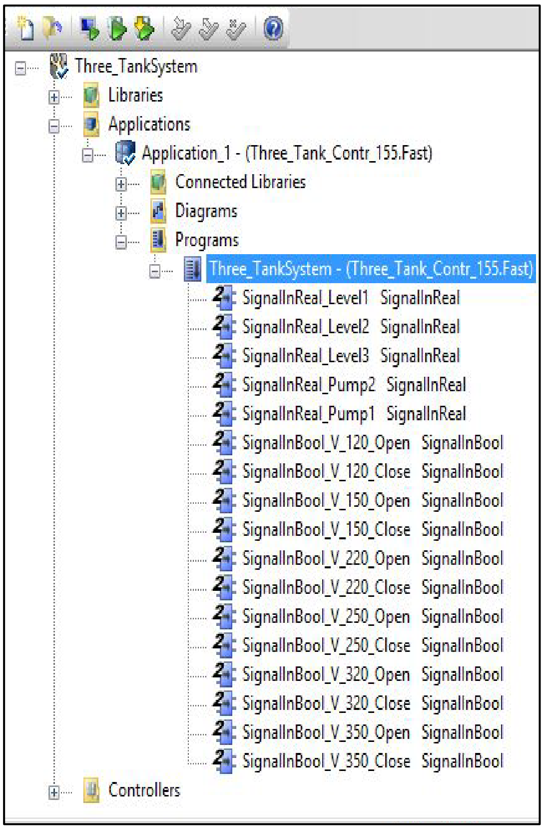

Figure 41. Connected signal blocks of the three tank system

7.3. Equipment: the mixing tank system

Mixing is a well-known unit operation process in industrial process engineering. It involves the manipulation of heterogeneous intakes to make them more homogeneous. Mixing is categorized into liquid – liquid, gas – gas, solid – solid, liquid – gas, gas – solid and multi phase mixing, which is used in a wide range of industries from oil & gas to factory processes. In this part, we discuss connection and configuration of a mixing tank with the familiar mixing system of homogenizing the temperature profile of water in a vessel that allows transferring of heat and mass fluxes. In the experimental part, the mixing tank is the third educational mini plant that is connected to the ABB 800xA. The equipment consists of a container, a pump, three sensors and four control valves. Table 9 lists the equipment in the mixing tank system, connections and the equipment tags.

The process is followed by two control input valves for hot and cold water (FC-101 & FC-201). The system is equipped with a circulation line as well a pump to drain the container faster, these two lines are also facilitated with two control valves (FC-402 & FC-502). Three temperature sensors indicate the temperatures of hot and cold water as well as the temperature of the mixture inside the container. Four process flow lines including two water inputs, circulation and the outflow lines are accompanied with magnetic flow meters to indicate the flow rate of water. In addition, the water pressure after the pump is defined and encoded as PT-305 to ensure the pump is not damaged due to water shortage.

Table 9. Equipment tags in mixing tank system

Equipment	**P&ID Tag / System Variable**	**Application**	**Specification**	**Card in the ABB Cabinet/ Active Channel**
Container	V300	-		-
Pump	P306 / M-304	Pump Switch	Digital Signal Output	DO801
Control Valve	V-101 / FC-101	Valve Controller	Analog Signal Output	AO801
	V-201 / FC-201	Valve Controller		
	V-401 / FC-401	Valve Controller		
	V-501 / FC-501	Valve Controller		
Sensors/Valves	LTC-301	Tank Level	Analog Signal Input	AI801
	QT-302	Water Conductivity		
	PT-305	Water pressure after pump		
	TT-103	Cold Water Temp.		
	TT-203	Hot Water Temp.		
	TT-303	Inside Tank Temp.		
	FT-102	Magnetic Flow Measurement, CW*		AI820

	FT-202	Magnetic Flow Measurement, HW*		
	FT-402	Magnetic Flow Measurement, Outflow		
	FT-502	Magnetic Flow Measurement, Circulation Line		
Pipe	25HW001* & 25CW002* 30PF003 to 30PF006*	-	DN 25 & DN 30	-
*HW: Hot Water / *CW: Cold Water / *PF: Process Flow Size(mm) + Flow + No. of pipe + Material of Pipe (unknown) 30 (mm) + Process Flow (PF) + 003				

Fig. 42 presents the P&ID of the mixing tank. The figure shows that hot and cold water are fed into the system by the PI-controllers FC-101 and FC-201, and the temperature of the flows are sent back by the analog signal to the ABB PLCs. The PI-controller FC-501 adjusts the circulation line back to the tank. Moreover, the cascade controller FC-402 regulates the drain of the vessel with LTC-301 and FT-402 as the master and the slave of the controller, respectively. The controllers and sensors continuously check specific conditions of the system to avoid overflow of the tank and the pump to run empty which can cause mechanical damage.

Fig. 43 presents the user interface of the mixing tank as a part of the workstation. The elements of the interface are provided by the Aspect server which enables the access of variables in the Controller Builder and the graphic builder. The interface streams live data for the user and compiles alarms / events, provides diagrams and detects the connection errors of the system. The system has the main switch OFF that in case of emergency, it shuts down the pump, closes the input and circulation lines and opens the drain line to empty the tank.

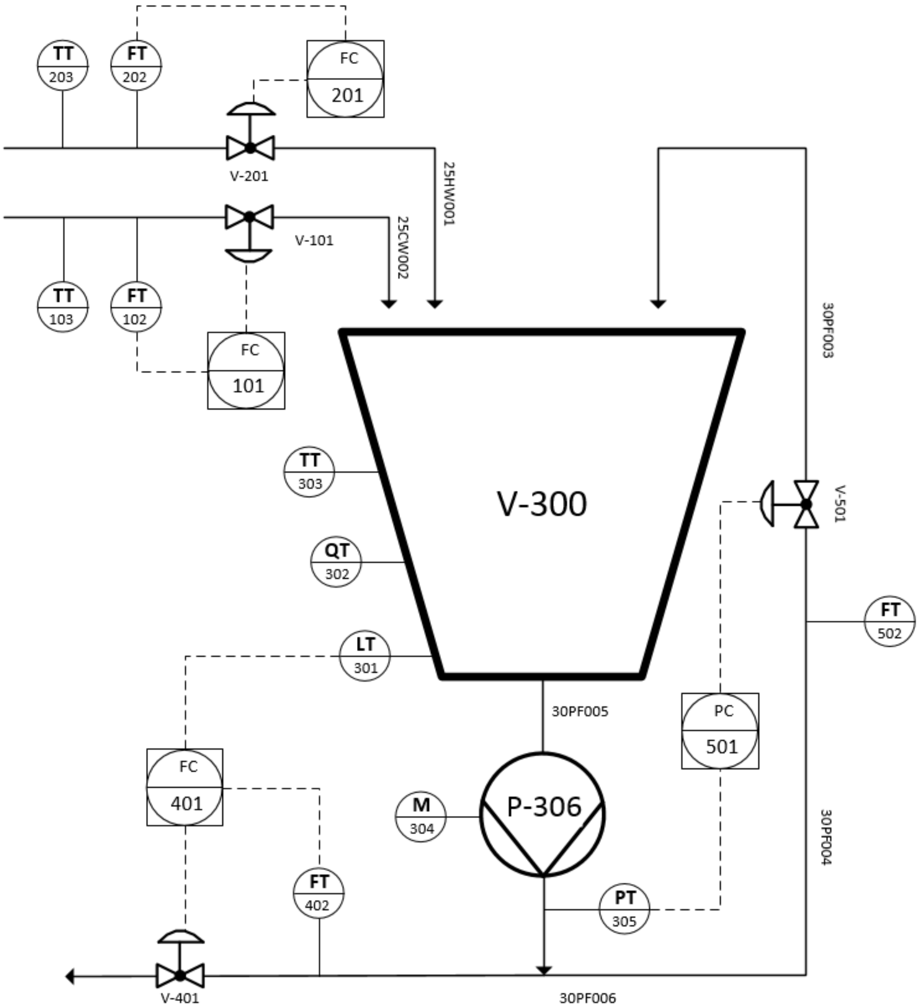

Figure 42. Mixing Tank System P&ID

Fig. 44 shows the Control Builder M Professional with IP 172.16.4.151 and 152 that is compiled with the project name 'ProjectWork_BJ_MixT'. Similar to the other mini plants, the physical connections are defined in the 'Controllers' section which includes the cards and the local variables while the global variables are introduced in the 'Applications' part of the controller builder. The libraries support communications between the 'Controllers' and 'Applications' with the predefined routines.

Fig. 45 shows the configured cards and their variables. AI801 receives the temperature, pressure and quality signals while AI820 handles the flow transmitter inputs. DO801 and AO801 send the signals for the pump and the controllers, respectively. These cards are defined and configured in ModuleBus of the controller.

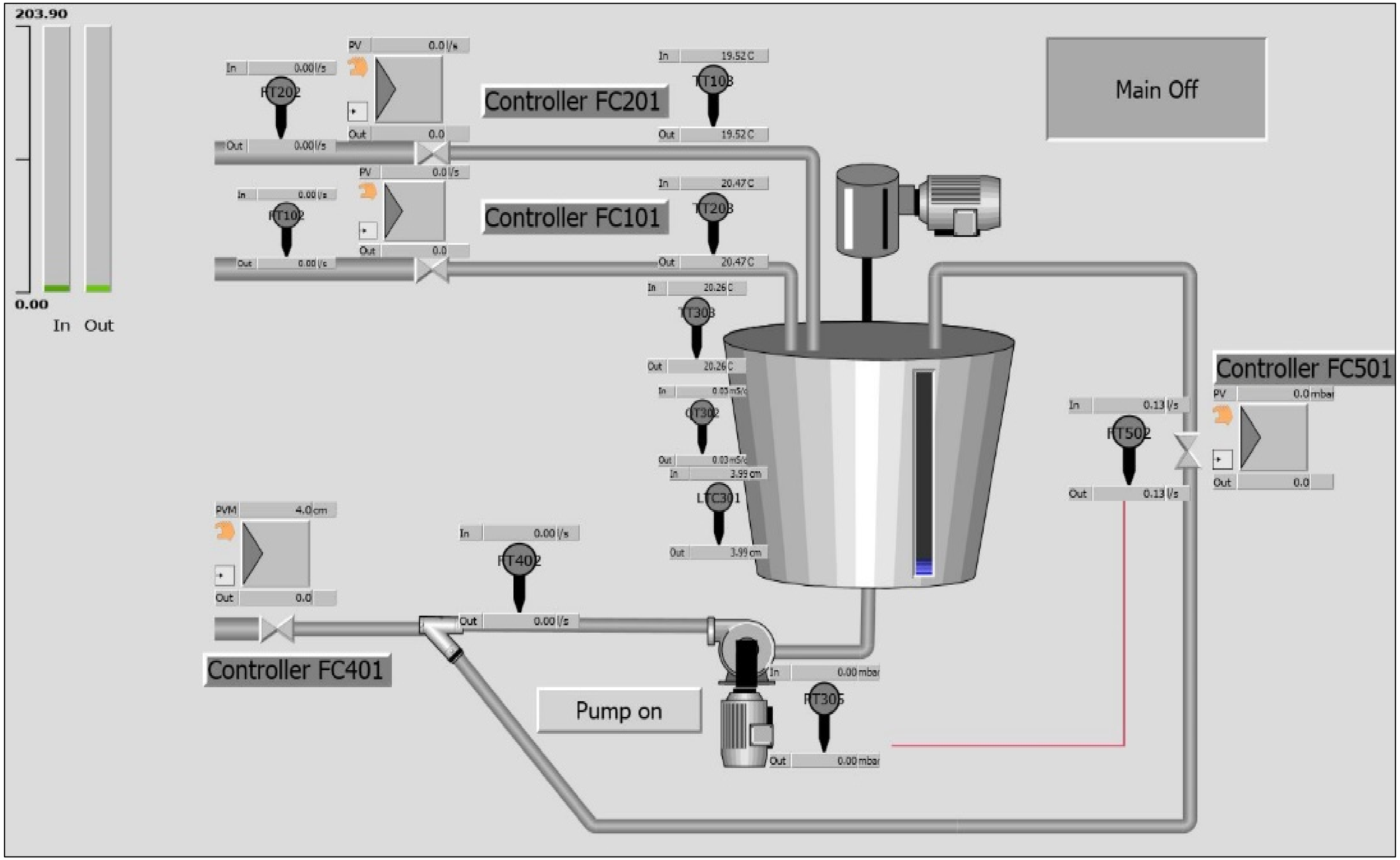

Figure 43. Human Machine Interface of the mixing tank system

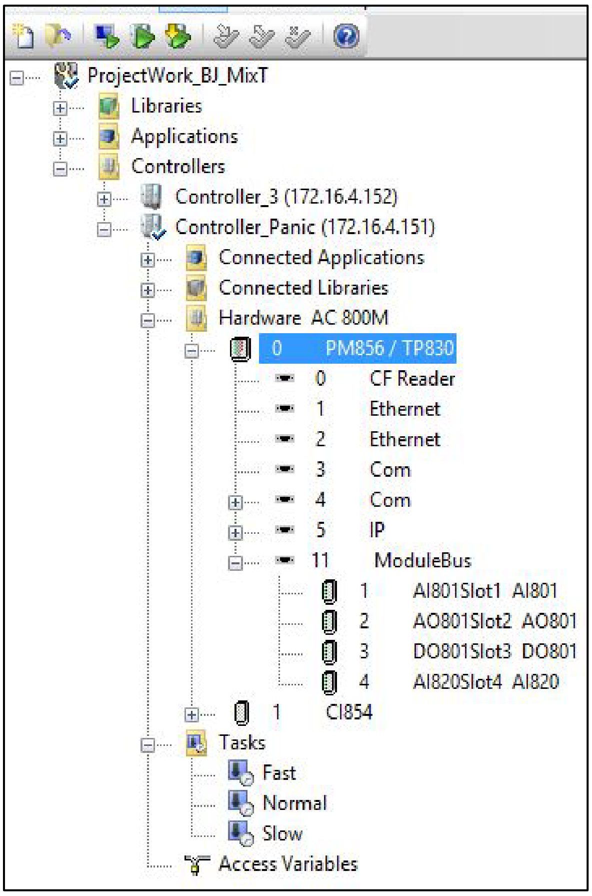

Figure 44. Controller builder of the Mixing Tank System

Signals of the measurement need to be introduced to the ABB system to avoid warning and overlaps. The signal blocks specify each signal with the additional local variables and use the connected libraries to enable the communication between the ABB servers and the equipment. Fig. 46 shows the defined signal blocks in the Applications section where the controllers are programmed and the signals of the transmitters are configured with a fast controller mode.

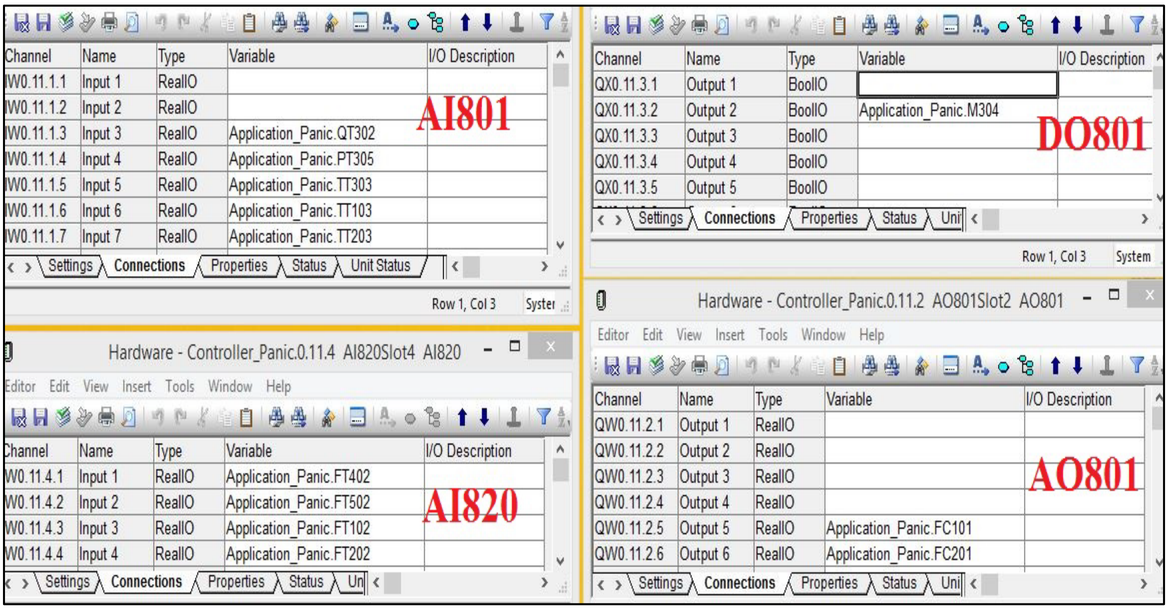

Figure 45. I/O cards with the variables for the mixing tank system in the ABB control system

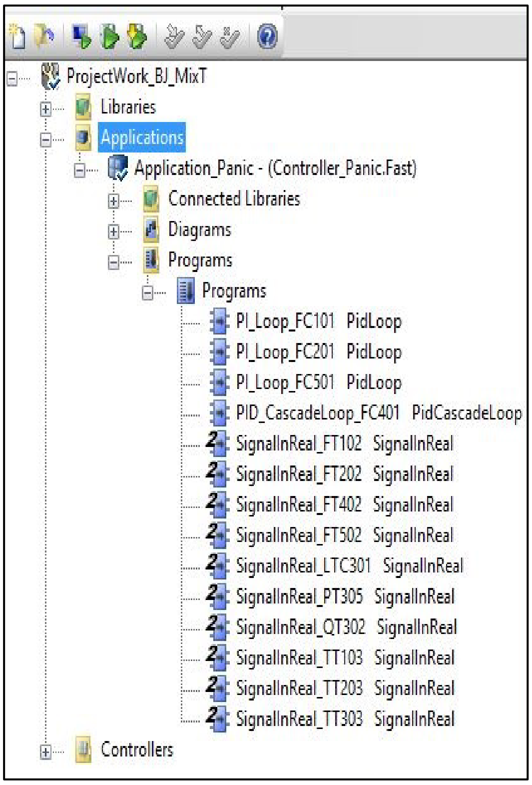

Figure 46. Signal blocks of the mixing tank system

7.4. OPC UA wrapper test

The OPC Unified Architecture (UA) server exposes the ABB configuration and hierarchy for the OPC UA client through the OPC DA. Therefore, the old OPC DA is accessed by the OPC UA which features a unified platform and architecture for different automation vendors to enable device to device communication. The OPC DA and UA are compared in the literature review and the relation between them is described. In this part, the concept is implemented and further tested with the mixing tank example. Fig. 47 presents the relation between the OPC UA wrapper and the ABB System 800xA. As the figure shows, the OPC UA client has the access to the aspect server and its hierarchy through the Domain Name Server (DNS). This client can be installed inside the ABB network or as a stand alone client.

Fig. 48 shows the tested access of the hierarchy in the 'OPC Unified Architecture Client' which was built under the system project. The figure presents one of the Boolean variables of the mixing tank system and the control network of the ABB 800xA along with all of its pre-built projects which are available in the client side. Fig. 49 shows the server 'MatrikonOPC UA Wrapper for COM OPC Servers' which provides the URL for connecting to the client. This general URL enables any OPC UA client to communicate with the OPC UA server and stays synchronized as long as the server URL is valid.

The OPC UA server is installed in the Connectivity or Aspect server of the ABB 800xA, and therefore has access to ABB configuration of the projects, monitoring and the system setup. In this technique, any authorized OPC UA client (e.g. OPC UA cloud client) from outside of the ABB network can communicate with the system and implement controlling methods. In comparison with the old OPC DA which was closed and limited controlling environment for ABB 800xA, such technology makes the ABB control system more flexible to be accessed from outside of the network and opens various controlling options.

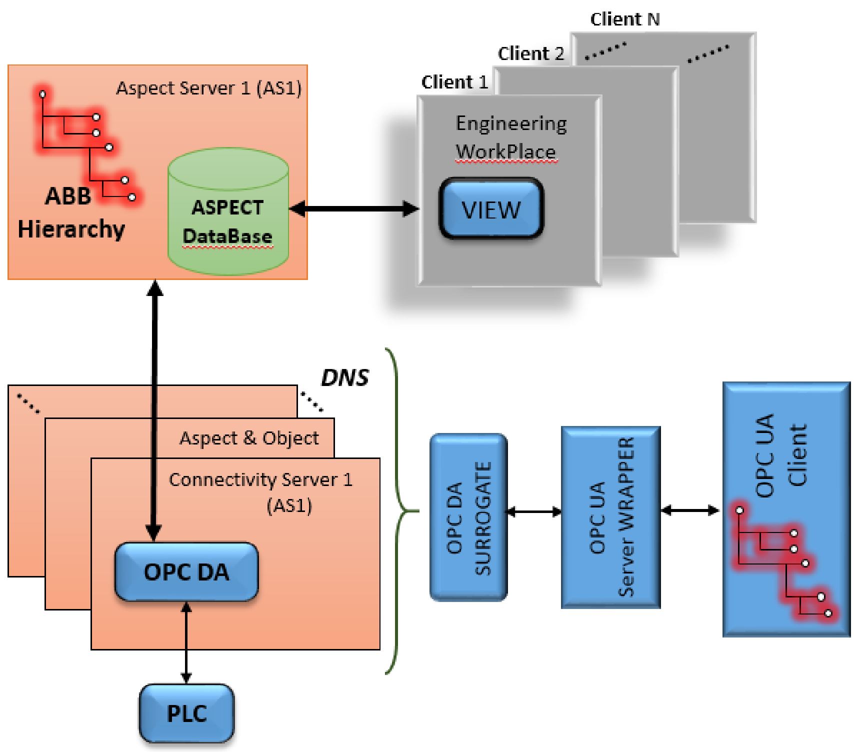

Figure 47. Architecture of the ABB servers with their connection to the OPC UA

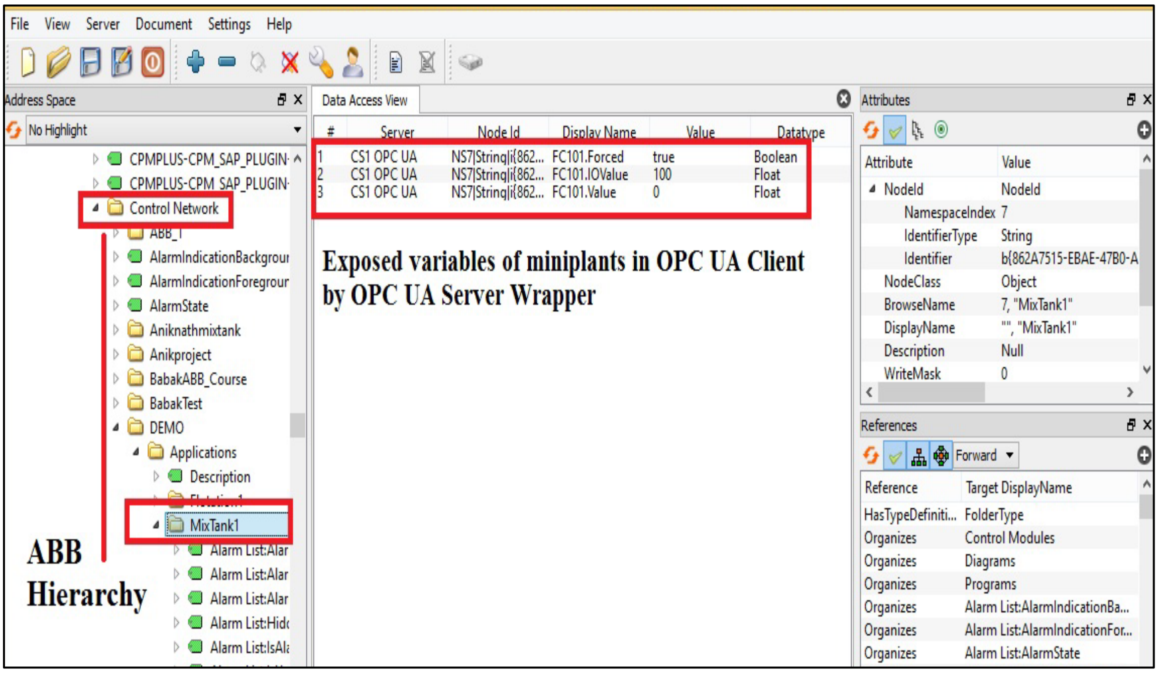

Figure 48. The access of the OPC UA client to the ABB hierarchy, Mix Tank1 test

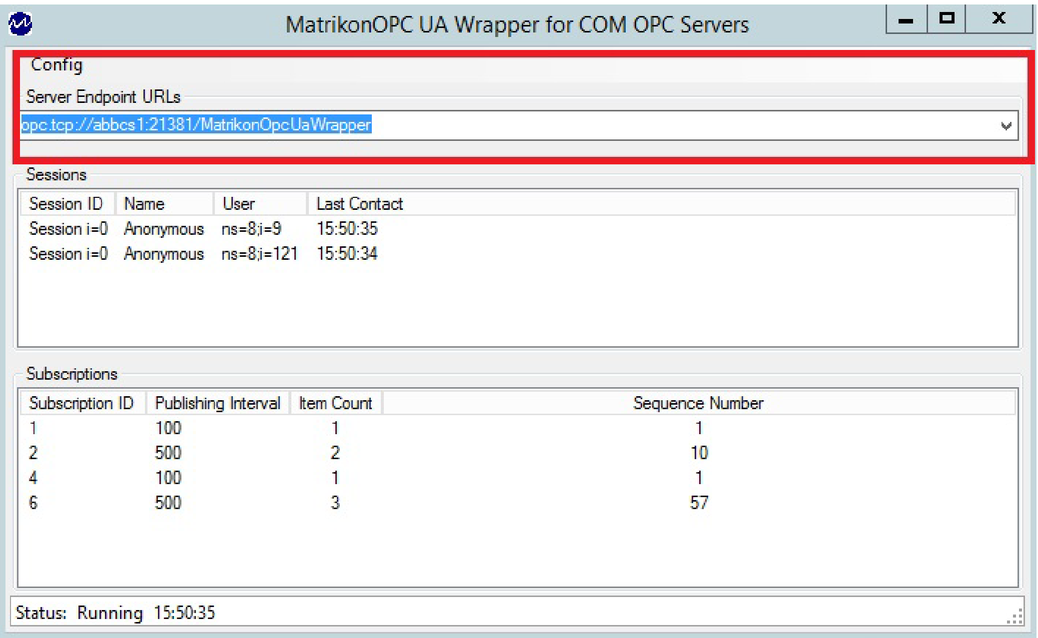

Figure 49. Provided URL from the OPC UA server inside the connectivity server

8. Conclusion and Discussion

In this thesis, the three mini plants were connected, configured and tested. The plants were a part of an architecture that enabled cloud space, 5G wireless connectivity and OPC UA connection. Furthermore, the setup was configured in the ABB 800xA control system and the OPC UA server / client was installed to test its access to the old OPC DA surrogate. During the thesis, the major obstacle was the break down of the main ABB server which was resolved by utilizing the duplicated feature of the main servers.

The first mini plant was heat exchangers with nineteen measurements and six valves which were connected, configured and simplified to TRUE for cocurrent and FALSE for countercurrent mechanism. The challenges were connecting four pneumatic valves and synchronizing the pneumatic references in the ABB system (which has digital and analog references) by an external conversion cabinet. Moreover, the heat exchanger system did not have any manual so the piping, equipment arrangements and the connections were mapped and configured based on try and error. The system was blocked in two points that were resolved by maintenance. The heat exchanger system provides the opportunity of studying control algorithms for four parallel heat exchangers. Different fluid types (i.e. different viscosities and specifications) can be studied since the heat exchangers are parallel and different from one another. The heat exchanger study is a continuous process and one of the most important cases studies for industry since it directly affects consumed energy and relates to the pinch analysis and heat integration that optimizes plant energy consumption. It is noteworthy that even one percent optimization of energy consumption in heat exchangers makes huge difference in long-term processes since they are the heart of heat transfer phenomena.

The three tank system was the second mini plant with eleven measurements that were connected and configured in the ABB 800xA. The challenges of this batch process unit were the configuration of six digital valves and two analog diaphragm pumps (with non-compatible references to ABB) which were fixed by adding two sets of electrical kits to make it compatible with the ABB 800xA. This system is provided by Amira co. with its isolated client, software and interface, but this mini plant is connected and configured in the ABB 800xA which is an industrial control system with five PLC programming languages. The system provides the study of the three cylinder tanks in series and the effect of disturbances which in this case are the leakage valves.

Thirdly, the mixing tank pilot with seventeen measurements was connected to enable the mixing phenomena study. Mixing is a common study case in automation laboratories and in this system, other measurements like level, temperatures, heating and circulation were considered. The connection and configuration of this system was checked and its edge conditions like the maximum and minimum level of water were tested. This mini plant provides the study of batch and continuous mixing by controlling the inputs, output and the circulation line. In addition to this work, the user manual for each mini plant is provided to describe the connection and the configuration of the setup.

This modern teaching environment enables practical teaching for students to test and practice industrial problems and to provide solutions with automation concept. Teaching process has a supervised technique with project works and assignments to groups of students. Furthermore, this modern teaching environment has the latest technologies like OPC UA, 5G and cloud computing in which students can challenge future automation problems and find solutions with these latest tools and technologies.

From research point of view, the set up enables advanced control algorithms, data analytics and many cloud services that can be tested with automation logics. By adding wireless sensors and smart measurements, the mini plants are potential to act as a cyber-physical system. In addition, different cloud services including network slicing, cloud computing and cloud database can be further studied with this setup. At the field device level, scheduling of the processes and optimized workloads for collaboration between mini plants and machinery resources (i.e. mini plants) can be tested via cloud services.

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